Universidade de Aveiro Departamento de Engenharia Civil
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BÁRBARA CARINA GONÇALVES MARINHO

ALIMENTAÇÕES ARTIFICIAIS COMO SOLUÇÃO DE DEFESA COSTEIRA: ABORDAGENS DE MONITORIZAÇÃO E MODELAÇÃO

ARTIFICIAL NOURISHMENTS AS A COASTAL DEFENSE SOLUTION: MONITORING AND MODELLING APPROACHES

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Tese apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Engenharia Civil, realizada sob a orientação científica do Doutor Carlos Coelho, Professor Auxiliar do Departamento de Engenharia Civil da Universidade de Aveiro, e coorientação científica do Doutor Magnus Larson e do Doutor Hans Hanson, Professores Titulares do Departamento de Engenharia e Recursos Hídricos da Universidade de Lund.

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I dedicate this work to my entire family, who has unconditionally supported me along the way, especially to my parents and sisters. May this work inspire my nephew and nieces to pursue their dreams and transcend further goals beyond this one.

o júri

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palavras-chave

trecho costeiro Barra-Vagueira, dragagem, actividades de deposição, evolução do perfil de praia, CS-model, resposta submersa, sistema de duas barras, tomada de decisão

resumo

Atualmente verifica-se um crescente interesse internacional por soluções de engenharia ambientalmente sustentáveis, capazes de combater a erosão, aumentar a largura da praia e manter a segurança das zonas costeiras. Ao longo das últimas décadas, tem-se assistido a uma mudança de paradigma no que toca à política de proteção da costa, que tem cada vez mais privilegiado o recurso às alimentações artificiais em detrimento das tradicionais estruturas de defesa costeira pesada.

Esta dissertação começa com uma revisão da literatura sobre a passada *vs* presente evolução do litoral português, dando ênfase a aspetos relevantes da gestão costeira (estruturação e processo de tomada de decisões politicas), bem como as principais estratégias de proteção que têm sido discutidas no contexto das futuras propostas de adaptação para as zonas costeiras, servindo para destacar os principais desafios e problemas de algumas regiões do litoral português. Como tentativa de disseminação do conhecimento científico acumulado sobre o comportamento das alimentações artificiais, este estudo foi direcionado para análise de um conjunto de dados de campo recolhidos no âmbito de um programa de monitorização estabelecido para cumprir com a legislação portuguesa e a política nacional de gestão para controlo dos impactos ambientais associados ao uso combinado de operações de dragagem e deposição na vizinhança de portos marítimos. Considerando o melhoramento da capacidade de modelação numérica, um objetivo igualmente importante para se garantir uma boa previsibilidade da evolução de praias alimentadas, nesta dissertação, um foco especial é também dado ao estudo da evolução do perfil transversal de praia, uma vez que a resposta das alimentações estão intrinsecamente relacionadas com a dinâmica sedimentar natural. Foi apresentado e aplicado um modelo numérico recente e inovador, que segue uma descrição simplificada da evolução do perfil transversal de praia (incluindo a erosão/recuperação da duna, galgamento e troca de material entre a porção emersa/submersa) ao caso de estudo da costa de Aveiro e para uma análise de sensibilidades no contexto de múltiplos cenários hipotéticos de alimentações artificiais. Este modelo foi posteriormente explorado via um dos módulos que o integra – a sub-rotina da troca de material entre a berma e a porção submersa – conduzindo a uma versão melhorada do modelo. Atenção foi dada à modelação numérica do comportamento submerso do perfil, a fim de realisticamente descrever os efeitos do transporte dos sedimentos das barras em direção à praia e vice-versa, envolvendo evolução de barras naturais e artificiais (de alimentação). Os desenvolvimentos teóricos foram testados e validados através de dados de campo disponíveis para três casos de estudo nos EUA. No geral, resultados desta aplicação mostraram-se prometedores, demonstrando o potencial de modelos simples e robustos para reproduzir as principais tendências no transporte transversal de sedimentos a longo-prazo. Esta tese constitui um contributo no sentido do aumento do conhecimento sobre as alimentações artificiais de praia, servindo como suporte aos órgãos gestores do litoral na tomada de decisão.

keywords

Barra-Vagueira coastal stretch, dredging, disposal activities, beach profile evolution, CS-model, subaqueous response, two-bar system, decision-making

abstract

A growing-interest for sustainable environmental engineering solutions able to combat erosion, enhance coastal safety and increase beach width is currently undergoing worldwide. Portugal is one of the countries that follow this pattern. Over the past few decades, a paradigm shift from “fighting” the forces of nature via hard engineering structures to “working with nature” solutions has emerged. Artificial sand nourishments have been in focus and regarded as a preferred method to mitigate erosion and maintain the coastline.

This dissertation starts with a literature review about the past *vs* present evolution of the Portuguese littoral, giving emphasis to relevant aspects concerning its management (legal status and policy making), as well as to the coastal adaptation strategies that have been under discussion in the context of the future proposals for coastal protection, serving also to highlight the main problems and challenges currently faced by many coastal regions in Portugal.

As an attempt to disseminate knowledge regarding the behavior of artificial nourishment operations, this study was further directed to assess a set of monitoring data, originally established to meet the Portuguese legislation and national policy on coastal management for controlling of the environmental impacts associated to the combined use of dredging and disposal activities, in the vicinity of harbors.

Considering the improvement of the numerical modelling capacity, an equally important goal for achieving good predictability of the nourished beaches evolution, in this dissertation special focus was also given to the study of the beach profile change, as the beach fill responses are intrinsically related to the natural beach sediment dynamics. A recent and innovative numerical model with a simplified long-term description of the beach profile evolution, accounting for dune erosion and recovery, overwash/breaching, and the exchange of material between the bar and the berm has been herein applied for the Aveiro coast and targeted for a sensitivity test in the context of hypothetical nourishment interventions undertaken on an open sandy beach. This model was later explored via one of its integrated modules – the bar-berm material exchange sub-routine – yielding to an improved CS-model. Emphasis was given to the numerical modelling of subaqueous beach profile behavior in order to realistically describe the effects of the sediment release from longshore bars towards the beach and vice-versa, encompassing bar evolution, response of feeder mounds and the coupling between the subaerial and subaqueous changes. The theoretical developments were tested and validated against existing high-quality data from different field sites in USA. Overall, outputs of the application of the model to these three US case studies, look promising, demonstrating the potential for using rather simple models to quantitatively reproduce the main trends in the cross-shore sediment exchange taking place for longer timescales. This thesis constitutes a step forward the increase of knowledge in the topic of artificial nourishments, serving to support coastal engineers and managers at the decision-making.

Appended papers

The development of this doctoral dissertation has resulted in four manuscripts that have been submitted/published in four distinct scientific international journals. The papers are appended at the end of this document.

Paper I. Palalane, J., Fredriksson, C., **Marinho, B.**, Larson, M., Hanson, H., Coelho, C. **(2016)**; *Simulating Cross-shore Material Exchange at Decadal Scale. Model Application*; Coastal Engineering, Elsevier, 116, 29-41 pp.

http://dx.doi.org/10.1016/j.coastaleng.2016.05.007

Author's contribution: The author has implemented the model for one of the study sites (Aveiro, Portugal) and was the main contributor to the writing of the corresponding section, providing also comments and participating in the review of the whole article.

Paper II. **Marinho, B.**, Coelho, C., Larson, M., Hanson, H. **(2017);** *Short- and Long-Term Responses of Nourishments: Barra-Vagueira Coastal Stretch, Portugal*. Journal of Coastal Conservation, Springer, 22(3), 475-489 pp.

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Author's contribution: The author was the main contributor to the writing of all manuscript sections and to the discussion regarding the main findings of the paper.

Paper III. **Marinho, B.**, Coelho, C., Larson, M., Hanson, H. **(2018);** *Monitoring the Evolution of Nourished Beaches Along Barra-Vagueira Coastal Stretch, Portugal*. Ocean & Coastal Management Journal, Elsevier, 157, 24-29 pp.

https://doi.org/10.1016/j.ocecoaman.2018.02.008

Author's contribution: The author developed a data processing analysis, contributing to the writing of all sections of the manuscript as well as to the discussion of the main findings and final revision of the paper.

Paper IV. **Marinho, B.**, Coelho, C., Larson, M., Hanson, H. **(2017);** *Cross-shore modelling of nearshore bars at a decadal scale.* Marine Geology, Elsevier (under review).

Author's contribution: The author participated in the model development ant its implementation at all the study sites, in the discussion, writing, and final review of the whole article.

Other related publications

Conference Proceedings

In parallel to the development of the previous manuscripts, distinct parts of the present dissertation have been disseminated by the coastal community in international scientific meetings around the world. The main scientific contributions to these international research meetings are described below:

Marinho, B., Larson, M., Coelho, C., Hanson, H. (2018); Long-term Coastal Evolution Modelling of Longshore Bars; ICCE'18 - Proceedings of 36th International Conference on Coastal Engineering, Baltimore, USA, 30th July to 3rd August (abstract).

Marinho, B., Larson, M., Coelho, C., Hanson, H. (2018); Overview of the Coastal Zones and Its Management in Portugal; EGU'18 – European Geosciences Union, Vienna, Austria, 8th to 13th April (abstract).

Marinho, B., Larson, M., Coelho, C., Hanson, H. (2017); *Modelling Multi-Bar System at Decadal Scale*; RCEM 2017 – 10th Symposium on River, Coastal and Estuarine Morphodynamics, Trento, Italy, 15th to 22nd September (abstract and poster).

Marinho, B., Coelho, C., Larson, M., Hanson, H. (2017); *Simulating Cross-Shore Evolution Towards Equilibrium of Different Beach Nourishment Schemes*; Proceedings of the Coastal Dynamics 2017, Working with Nature, Helsingør, Denmark, Paper 121, 1732-1746.

Marinho, B., Coelho, C., Larson, M., Hans, H. (2016); *Short- and Long-Term Responses of Nourishments: Barra-Vagueira Coastal Stretch, Portugal*, Littoral 2016 – The Changing Littoral. Anticipation and Adaptation to Climate Change, 25th to 29th October, Biarritz, France, p. 139 (abstract and poster).

Marinho, B., Coelho, C., Larson M., Hanson, H. (2015); *Monitorização da Evolução Morfológica, Sedimentar e Batimétrica do Trecho Costeiro Barra-Vagueira: Correlação com a Agitação e Intervenções Costeiras*, VIII Congresso sobre Planeamento e Gestão das Zonas Costeiras dos Países de Expressão Portuguesa, 14th to 16th October, Aveiro, Portugal, Paper 2A3_Artigo_022, 15p. ISBN 978-989-8509-13-0 (in portuguese).

Marinho, B., Coelho, C., Larson, M., Hanson, H. (2015); *Aplicação da Análise EOF ao Trecho Costeiro Barra-Vagueira*; VIII Symposium on the Iberian Atlantic Margin, Málaga, Spain, 21st to 23rd September, 2015 (extended abstract, in portuguese).

Chapters in National Books

Marinho, B., Coelho, C., Larson, M., Hanson, H. (2018). *Modelação Numérica da Aplicação de Dragados no Reforço do Perfil Transversal de Praia*, Chapter III.3, 131-151 pp. ISBN 978-972-789-535-9.

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List of Abbreviations

AHA	Aveiro Harbor Administration
APA	Portuguese Environment Agency (*Agência Portuguesa do Ambiente*)
ARH	Administrative Hydrographic Regions
ASN	Artificial Sand Nourishment
CA	Common Area
CA1	Common area to all surveys collected for DA1
CA2A	Common area to all surveys collected for DA2, with exception of the survey of Jan-14
CA2B	Common area to all surveys collected for DA2, with exception of Dec-10, Nov-11, Nov-13 and Jan-14
CCDR	Commissions of Coordination and Regional Development (*Comissão de Coordenação e Desenvolvimento Regional*)
CD	Chart Datum
COSMO	Monitoring Program of the Portuguese Coastal Zones (*Programa de Monitorização da Faixa Costeira de Portugal Continental*)
CS	Current Situation
CS	Cross-Shore
DA1	Dumping Area 1
DA2	Dumping Area 2
DGAM	General Direction of the Maritime Authority (*Direção Geral da Autoridade Marítima*)
DGPM	General Direction of the Sea Policy (*Direção Geral de Política do Mar*)
DGRM	General Direction of the Natural Resources, Security and Maritime Services (Direção Gerald de Recursos Naturais, Segurança e Serviços Marítimos)
DGT	General Directorate of the Territory (*Direção Geral do Território*)
DIA	Environment Impact Statements (*Declaração de Impacto Ambiental*)
ENGIZC	National Strategy for Integrated Coastal Zone Management (Estratégia Nacional de Gestão Integrada das Zonas Costeiras)
EOF	Empirical Orthogonal Functions
FRF	Field Research Facility
GeoE	Geographic Institute of the Army (*Instituto Geográfico do Exército*)
GIS	Geographic Information System

GPD	Gross Domestic Product
GPS	Global Positioning System
GTL	Littoral Working Group (*Grupo de Trabalho do Litoral*) formed in 2014 under the Legislative order nr. 6574/2014 of the Ministry of the Environment in 20th May
GTS	Sediment Working Group (*Grupo de Trabalho para os Sedimentos*) constituted in 2015 under the Legislative order nr. 3839/2015 of the State Secretary of the Environment in 17th April
HA's	Harbor Administrations
ICNF	Institute of the Conservation of the Nature and Forests (*Instituto da Conservação da Natureza e das Florestas*)
ICZM	Integrated Coastal Zone Management
IDW	Inverse Distance Weighting
IH	Hydrographic Institute (*Instituto Hidrográfico*)
INE	National Institute of Statistics (*Instituto Nacional de Estatística*)
INSPIRE	INfrastructure for SPatial InfoRmation in Europe
IPMA	Portuguese Institute of the Sea and Atmosphere (*Instituto Português do Mar e Atmosfera*)
IS	Information Systems
LG	Longshore
LIDAR	Light Detection And Ranging
LMG	Last Maximum Glacial
LNEC	National Laboratory of Civil Engineering (*Laboratório Nacional de Engenharia Civil*)
LNEG	National Laboratory of Energy and Geology (*Laboratório Nacional de Energia e Geologia*)
LWT	Large Wave Tank
MLLW	Mean Lower Low Water
MSFD	Marine Strategy Framework Directive
MSL	Mean Sea Level
NAOAA	National Oceanic Atmospheric Administration
NGVD	National Geodetic Vertical Datum
P1-P12	Surveyed beach profiles covering the S. Jacinto-Vagueira coastal stretch
PIANC	Permanent International Association of Navigation Congresses

POC	Coastal Zone Management Program (*Programa da Orla Costeira*) – new portuguese management tool
POOC	Coastal Zone Management Plans (*Planos de Ordenamento da Orla Costeira*) – old portuguese management tool
PS	Past Situation
PT	Portugal
RTK	Real-Time Kinematic
SDSI	Special Data Storage Infrastructure
SGPS	Management Society of Social Participations (*Sociedade Gestora de Participações Sociais*)
SIARL	Administration System of the Littoral Resources (*Sistema de Administração do Recurso Litoral*)
SLR	Sea Level Rise
SNIG	National Geographic Information System (*Sistema Nacional de Informação Geográfica*)
SWL	Sea Water Level
USACE	US Army Corps of Engineers
WIS	Wave Information Studies
WwN	Working With Nature

List of Symbols

A	principal component scores from EOF analysis	-
A	empirical coefficient in the overwash model	-
C_B	empirical coefficient in the longshore bar model	-
C_c	adjustment coefficient to bar response for offshore transport	-
C_c^I	adjustment coefficient to inner bar response for onshore transport	-
C_c^0	adjustment coefficient to outer bar response for onshore transport	-
C_c^{off}	adjustment coefficient to bar response for offshore transport	-
C_c^{on}	adjustment coefficient to bar response for onshore transport	-
C_f	coefficient for frictional losses over the berm	-
C_S	impact formula empirical transport rate coefficient	-
D	data matrix from EOF analysis	-
D_B	vertical distance from mean water level to the dune foot	m
D_C	depth of closure	m
d_{50}	median sediment grain size	mm
E	principal components from EOF analysis	-
H_o	deep water wave height	m
H_1	wave height limit for the groups of waves that will break at outer bar depths	m
H_2	wave height limit for the groups of waves that will break at inner bar depths	m
H'	modified wave height for runup calculations	m
H_b	breaking wave height	m
H_c	critical wave height	m
H_s	significant wave height	m
H_t	extreme tidal projection (before h_t)	m
h_c	depth-to-bar crest	m
h_t	extreme tidal projection (after H_t)	m
L	eigenvalues values from EOF analysis	-

L_0	deep-water wavelength	m
m	coefficient in the longshore bar model	-
N	number of observations	-
q_B	subaqueous transport rate between the bar and the berm	$m^3/s/m$
q_D	sediment transport rate eroded from the dune (divided into q_L and q_S)	$m^3/s/m$
q_L	overwash transport	$m^3/s/m$
q_S	seaward transport resulting from erosion of the dune (backwash transport)	$m^3/s/m$
q_{WE}	equilibrium sand transport rate by wind	$m^3/s/m$
q_{WL}	wind-blown transport on the landward side of the dune	$m^3/s/m$
q_{WS}	wind-blown transport on the seaward side of the dune	$m^3/s/m$
R	wave runup height	m
s	dune height	m
$s_{máx}$	maximum dune height	m
T	wave period	s
T_p	peak wave period	s
T_{Hs}	wave period corresponding to H_s	s
T_t	time period between H_t and h_t	s
t	time interval between the previous extreme time and the interpolation moment	s
V_B	bar volume	m^3/m
V_B^I	inner bar volume	m^3/m
V_B^O	outer bar volume	m^3/m
V_{BE}	equilibrium bar volume ($=V_{BE}^{TOT}$)	m^3/m
V_{BE}^I	equilibrium inner bar volume	m^3/m
V_{BE}^O	equilibrium outer bar volume	m^3/m
V_D	dune volume	m^3/m
w	sediments fall speed	m/s
$X_{Bar,crest}$	bar crest distance to the shoreline	m
y_B	location of berm crest (represents the shoreline position)	m
y_L	location of landward end of the dune/barrier	m
y_S	location of seaward end of the dune/barrier (dune foot)	m

z_D	vertical distance from the dune foot level and the water level at each time step	m
z_t	sea water level at the moment after a high or low tide	m
α	ratio between the eroded dune volume going onshore (shoreward side) and offshore (berm)	-
$ß_F$	foreshore slope	rad
$ß_L$	landward slope of the dune/barrier	rad
$ß_S$	seaward slope of the dune/barrier	rad
Δ	coefficient expressing the spatial growth of wind transport rate	-
ΔV_D	dune volume mobilized by the waves	m^3/m
ΔV_L	volume of sediments mobilized by the waves over the dune crest to the shoreward side of the dune	m^3/m
ΔV_S	volume of sediments mobilized seaward by the waves from the dune to the berm	m^3/m
Δt	time step of the simulation	s
δ	ratio between the outer and inner bar volume at the equilibrium	-
δ_0	empirical coefficient in the two-bar model	-
ε	normalized least-square error	-
θ	offshore wave incident angle	º
λ	coefficient quantifying the rate at which the bar equilibrium volume is approached	s^{-1}
λ_0	bar response coefficient in the one-bar model	s^{-1}
λ_0^I	inner bar response coefficient in the two-bar model	s^{-1}
λ_0^O	outer bar response coefficient in the two-bar model	s^{-1}
Ω	dimensionless fall speed	-

CHAPTER 1

INTRODUCTION

Chapter structure

1.1. Background and problem statement
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1. INTRODUCTION

1.1. Background and problem statement

Erosion has become one of the biggest threats affecting the coastal zones worldwide, as 70% of the shorelines are retreating (Bird, 1985). Episodes of erosion-overtopping-breaching-inundation, causing destruction or threatening engineering walls, fields, roads, and even seaside villages, have been reported in several countries all over the world, *e.g.* Netherlands, Sweden, Denmark, U.K., Japan, Spain, Italy, Australia, China, USA and Portugal (Dean, 2002; Ojeda *et al.*, 2008; Castelle *et al.*, 2009; Yates *et al.*, 2009; Kuang *et al.*, 2011; Roberts and Wang, 2012; Pranzini and Williams, 2013; Anthony *et al.*, 2014; Brown and Nicholls, 2015; Burcharth *et al.*, 2015; Luo *et al.*, 2015; Oliveira, 2015; De Leo *et al.*, 2016; Luo *et al.*, 2016; Schipper *et al.*, 2016; Zhao *et al.*, 2017). Many causes related to the coastal erosion phenomenon have been under discussion not only by the scientific community but also by coastal engineers and managers, representing government agencies, in order to solve problems and establish sustainable coastal adaptation strategies. Generalized sediment deficit, sea level rise and other associated climate change effects, storm surge and shoreline profiling imbalances caused by human-driven activities have been regarded as the main protagonists behind the observed changes along the coast (Nicholls and Hoozemans, 1996; Genua-Olmedo *et al.*, 2016). All of these drivers allied to a generalized increasing population density towards the coastal zones as well as growing pressures from multiple industries have been resulting in a high level of risk for human beings, infrastructures and economical activities.

This worldwide situation has instigated a general demand for *working with nature* solutions, *i.e.*, sustainable coastal maintenance approaches able not only to cope with economic growth in urban areas, but also to preserve/maintain the ecosystem in which it operates, safeguarding this way future generations (Pranzini and Williams, 2013; Bergillos *et al.*, 2018). Along the past few decades, less damaging techniques such as artificial beach nourishments have been in focus due to their potential benefits for mitigating erosion, ensuring flood safety and increased beach width, as well as providing opportunities for recreation and nature-based activities. Although sand nourishments are conventionally faced as a high-potential soft protection measure against erosion, there is still little solid knowledge concerning its efficiency and performance along the project life, for different physical environmental contexts. When in the absence of engineering structures, the control over the nourished sand is minimal, and questions about the ultimate fate of the dump material still remain. This justifies the need to document and categorize effects of different natural actions and interventions carried out along the coast, enabling a learning-by-doing approach. The empirical knowledge is crucial for preliminary design of cross-shore and planform shape of the fills and their volumes to meet project design lifetime and minimize costs. Also, collecting field observations can shed light on the natural conditions that prompt the need for adapting the project design solution or developing potential alternatives (Capobianco *et al.*, 2002; Castelle *et al.*, 2009; Vacchi *et al.*, 2012, Marinho *et al.*, 2017a).

The establishment of monitoring programs in sandy shores is conventionally assumed as a starting point to understand present-day coastline evolution (Baptista *et al.*, 2014). Although follow-up programs are essential and should be faced as a first order of priority, often they are not well established, producing limited information related to the processes behind the beach dynamics. The importance of such information relays also on the development, calibration and validation of numerical models, which are important tools for predicting the beach evolution in the neighborhood of planned or existing engineering projects. Although laboratory tests can also offer an option to anticipate the resulting effect of different coastal protection interventions, sometimes they are not feasible. This is because usually large amount of funding are required and, as in the case of beach nourishments, they may also not be effective as the process of beach change is primarily caused by irregularities in the wave regime, which are difficult to accurately model in a laboratory scale.

Figure 1.1 shows an idealized model for an integrated coastal zone management (ICZM) policy in the format of a relational and equilateral triangle. Basically, the core of the problem relays on how to analyze and put into practice the three strategic pillars, in which the coastal management structure should be based on – 1) Coastal Evolution; 2) Coastal Interventions; and 3) Coastal Monitoring. ICZM is a very dynamic and iterative process that requires a good articulation of these three main variables. It should then embrace the full cycle of data collection, planning (in its broad sense), decision-making and monitoring, by following a participatory approach that encourages the cooperation of all the involved actors and stakeholders to assess the societal goals established for a certain coastal zone and to take actions to meet such goals.

By undertanding the physical processes behind the natural evolution of the coastal zones, the risks, the vulnerabilities, the exposure level, the costs and impacts of the human-driven activities over the long-term, managers may be able to develop an integrated approach, safeguarding all aspects of the coastal zones, including geographical and political boundaries, in an attempt to achieve sustainability. The typical diagnosis, unique and objective, should no longer exist, arising in place a coastal adapation strategie built upon multi-criteria and cost-benefit analysis as a way to concilate multiple interests, within the limits set by the natural dynamics (Figure 1.1).

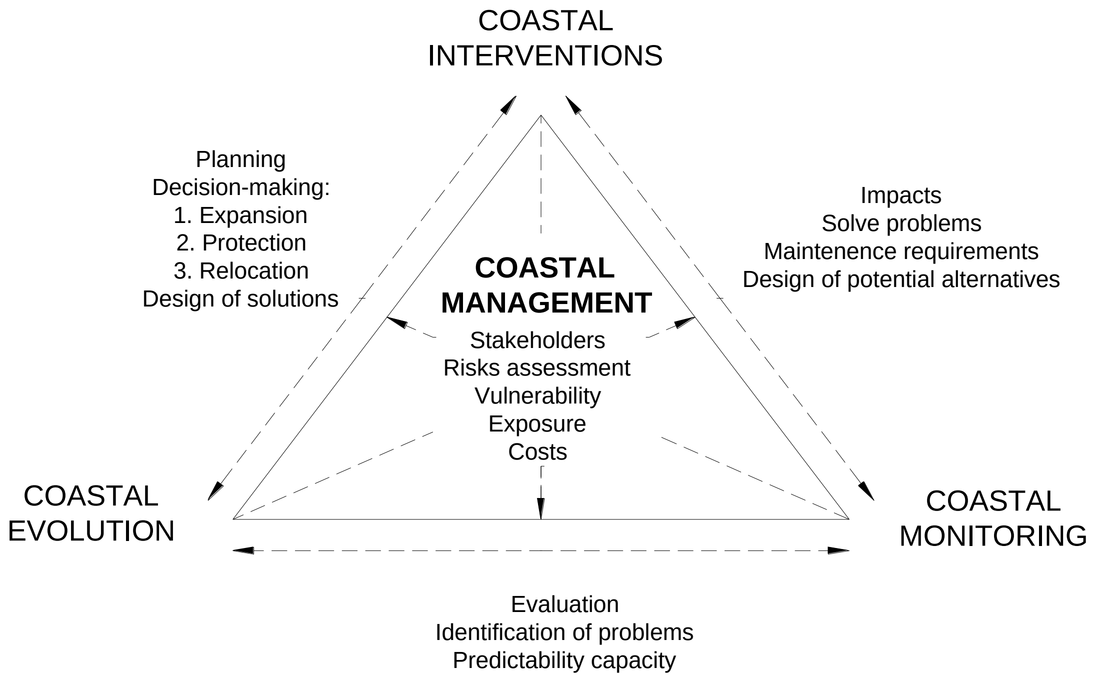


Figure 1.1. Triangle describing the coastal development process.

Aiming the dissemination of knowledge regarding the adaptation of coastal systems in the presence of artificial nourishment operations, this study started by assessing a set of monitoring data, originally established to meet the Portuguese legislation and national policy on coastal management (**Paper II, Paper III**), for controlling of the environmental impacts associated to the combined use of dredging and disposal activities in the vicinity of harbors. Taking as study case an intermediate to energetic hydrodynamic environment with a scarce natural sediment input, located on the northwest coast of Portugal, a set of correlated analysis are brought together as an attempt to assess the short- and long-term responses of several nearshore nourishments as well as the related-impacts to nearby sediment-starved beaches.

Prior to data analysis, relevant aspects concerning the general evolution of the Portuguese littoral (past and recent coastal interventions, morphological change, etc.) and its management as well as the coastal adaptation strategies under discussion for the future coastal protection are summarized as a way to highlight the main problems and challenges currently faced by many coastal regions in Portugal.

Considering the improvement of the numerical modelling capacity, an equally important goal for achieving good predictability of the nourished beaches evolution, special focus was also given to the study of the beach profile change as the main beach fill responses are intrinsically related to the natural beach sediment dynamics. While short-term responses usually refer to the initial adjustment of the fill and the redistribution of the nourished sand during high-energy events, long-term responses are mainly associated to the evolution of the topography towards new equilibrium conditions and the effect of gradients in the longshore sediment transport (Larson *et al.*, 1999).

Engineering and management needs are increasingly demanding sophisticated, robust, and reliable models able to reproduce faithfully the physical factors controlling the beach change at all time- and length-scales. In this context, a proper balance between physical descriptions from theoretical considerations and empirical information based on data and observations is the key for simulations addressing large areas and long time periods that will yield useful model results. Motivated by these facts, this thesis contributes also to the improvement of an innovative cross-shore numerical model, known as the CS-model, designed to simulate the beach-dune system evolution at a decadal scale (Larson *et al.*, 2016; Marinho *et al.*, 2017b). The CS-model was developed to fill the gap between a sediment budget approach and a detailed profile evolution model, in order to better account the main relevant cross-shore processes in a long-term perspective (Larson *et al.*, 2016; Palalane *et al.*, 2016). Emphasis was given to the numerical modelling of subaqueous beach profile behavior in order to realistically describe the effects of the sediment release from longshore bars towards the beach and vice-versa, encompassing bar evolution, response of feeder mounds and the coupling between the subaerial and subaqueous profile response. Efforts were made to expand the theory for the evolution of a single-bar to a two-bar system, where the volumes of individual bars and their response are modelled. The theoretical developments were tested and validated against existing high-quality data from different field sites in USA. The model was also employed to simulate the medium-term coastal evolution at the Aveiro coast and the behavior of multiple hypothetical artificial beach nourishment scenarios.

1.2. Objectives

The main objective of the present dissertation was to investigate the performance associated with artificial beach nourishments on the coastal environment, by taking as starting-point the monitoring scheme established by the Portuguese institutional board responsible for coastal zone management. To address this goal, the discussion of the adequacy of the monitoring plans becomes fundamental, and a significant part of the conducted research was redirected to the development of studies supported by coastal evolution numerical models. Aiming the improvement of the beach morphology change predictability in the presence or not of beach nourishments in a long-term perspective this dissertation intends to offer a tool to coastal engineers and managers in support of the decision-making.

Different development stages of this research encompassed data processing and analysis, numerical model development and application sustained by a set of field observations during monitoring campaigns.

To fulfill the main objectives, the following specific objectives were formulated:

1. Perform a short literature review to document coastal evolution in Portugal. Classify sediment dynamics and morphological change; summarize past coastal interventions and highlight observed problems and high-risk erosion areas.
2. Discuss the legal status and policy on coastal management in Portugal. Analyze administration responsibilities concerning coastal protection and their legal instruments. Describe the future measures and policies to improve the relation between land use and the coastal environment.
3. Compile and analyze available data concerning beach nourishments experiences, with special focus on the Portuguese littoral.
4. Examine the suitability of the monitoring programs built into the national legal coastal administrative system by taking as study case the Barra-Vagueira coastal stretch, located south of the Aveiro harbor.
5. Evaluate and interpret a set of monitoring data in order to relate morphological changes, evolution trends, sediment budgets, sediment transport gradients, and short- and long-term responses of nearshore nourishments to the incoming wave conditions.

6. Investigate the numerical approaches for simulating cross-shore sediment transport and long-term profile evolution, both for the subaerial and subaqueous portion of the profile.
7. Develop a subaqueous sub-model for simulating the evolution of a two-bar system, as well as the response of feeder mounds to incident waves and test it against available data.

1.3. Methods

As many engineering studies, the research methodology adopted to build knowledge presented in this dissertation falls largely into the empiricism, *i.e.*, acquisition of knowledge through past experiences and data collection with regard to certain mechanisms, events or phenomenon. In order to achieve the main goals established in this dissertation, different methods were adopted to address all the specific objectives as described below:

- Literature review to collect relevant information concerning coastal evolution in Portugal and its management as a way to open to a discussion about potential weaknesses and strengths of the national coastal zone monitoring policy.
- Data analysis and processing through the use of ArcGis tools and application of multivariate statistical method (Empirical Orthogonal Functions) to investigate the temporal and spatial patterns related to the sediment dynamics of artificial nourishments (**Paper II**, **III**).
- Model development to improve calculation approaches regarding subaqueous cross-shore material exchange at decadal scale and its further incorporation in a long-term profile evolution model (**Paper IV**).
- Model application as a mean to objectively measure the predictably capacity of the developed numerical approaches and its validation at selected sites (**Paper I**, **IV**).

A significant part of this research is built upon a set of field data, in connection with fill placements, as well as numerical studies which also require the availability of high-quality data sets for calibration and validation procedures. Although this thesis compiles several sets of available data for different sites around the world, the present study was somewhat subordinated to the quality of the instrumental collecting measurements, historical coastal evolution documentation, beach profile records and monitoring approaches adopted for spatial and temporal coverage.

1.4. Structure of the dissertation

The present dissertation develops in a monography format and is organized in seven chapters supported by a set of appended papers (see Figure 1.2).

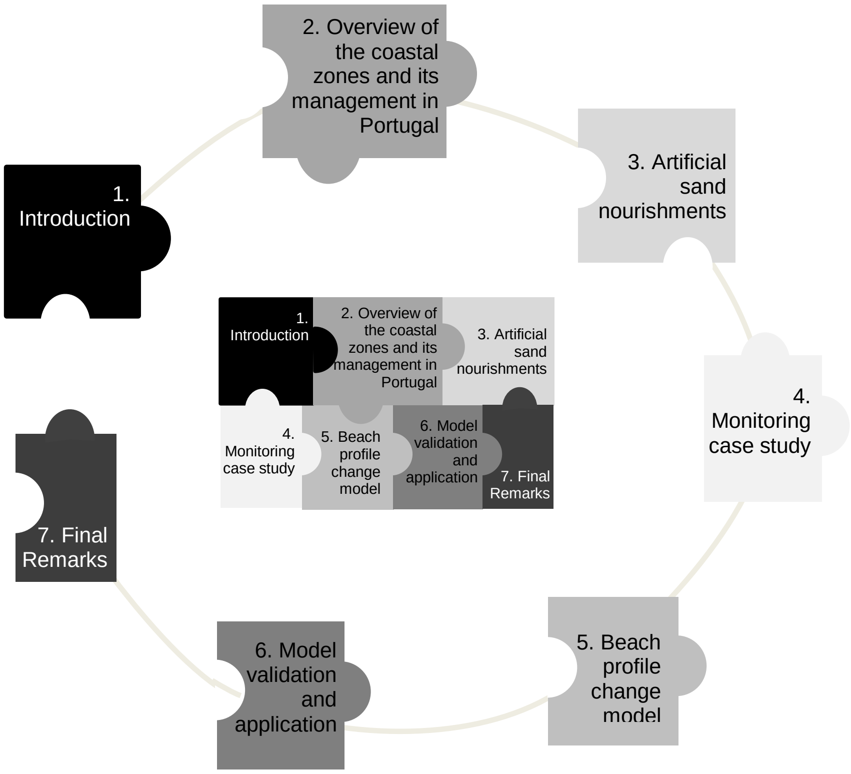


Figure 1.2. Structure of the dissertation.

Chapter 1 starts with a brief introduction, giving the background and stating the problems that highlight the importance of the study. The following chapters establish the connection to the main and specific goals defined for this thesis. Chapter 2 offers a general overview of the coastal zones and its management in Portugal, where special emphasis is given to the legal administrative structure, monitoring practices and the future coastal adaptation strategies that have been under discussion by the governmental agencies. Chapter 3 explores general cross-cutting issues related to artificial sand nourishments as a coastal protection measure, presenting some past and current applications along the Portuguese littoral as well as some discussion about costs, benefits and impacts. Chapter 4 is dedicated to the study of a regular-nourished coastal stretch with dredged sand (Barra-Vagueira coastal stretch, northwest coast of Portugal), where a set of correlated analyses are brought together in order to assess the morphodynamic evolution of the fills as well as their impacts related to nearby beaches. The study of the beach profile change is undertaken in chapters 5 and 6, by focusing on model development and application considering or not nourishment scenarios. Final conclusions are drawn in chapter 7, followed by potential recommendations for further research.

Some research results have been disseminated as follows in the appended papers:

Paper I (Palalane *et al.*, 2016) addresses the specific objective 6 by exploring an innovative simplified numerical approach based on a schematization of the beach profile shape that allows simulations of the beach-dune system evolution for large time-scales while keeping the model stability.

Paper II (Marinho *et al.*, 2017a) and **Paper III** (Marinho *et al.*, 2018a), in line with the specific objectives 4 and 5, analyze in deep a field dataset resulted from a national follow-up program established to control the impact of several dredging-disposal activities in the vicinity of a harbor – a symbiotic solution typically adopted to mitigate erosion in Portugal.

Paper IV (Marinho *et al.*, 2017c), in response to the specific objective 7, describes the development of a sub-model to simulate cross-shore exchange of material, with focus on two-bar systems evolution and feeder response of artificial bars.

CHAPTER 2

OVERVIEW OF THE COASTAL ZONES AND ITS MANAGEMENT IN PORTUGAL

Chapter structure

2. OVERVIEW OF THE COASTAL ZONES AND ITS MANAGEMENT IN PORTUGAL

Portugal (PT) is a country located in the southwest part of Europe, with territory at the western zone of Iberian Peninsula and archipelagos in North Atlantic. Its continental coast is bordered by the Atlantic Ocean along an estimated length of 987 km, constituting one of the most affected coastlines worldwide by the erosion phenomenon (Taveira-Pinto, 2004; Hinkel *et al.,* 2013; Pranzini and William, 2013; APA, 2016). According to the global study developed by Hinkel *et al.* (2013), addressing the long-term erosion due to sea level rise (SLR), PT ranks in the top 7 of the 166 coastal countries predicting high costs for forced migration of coastal residents, if no adaptation measures are taken to prevent erosion.

During the past few decades, the difficulty of reconciling the safety of people and assets with the benefits offered by natural coastal resources has been extremely exacerbated. Part of this situation is mainly attributed to the growing population density near the coast (with 75% of the inhabitants living in coastal municipalities), increasing capital investments (in coastal defense) and failing river sediment discharges (EUrosion, 2006; APA, 2016). The cost of mitigation actions has been increasing. Between 1995 and 2014, public expenditures dedicated to coastline protection against the risk of erosion and flooding have reached an estimated amount of 196 million euros (M€), whereas the cost of repairing the damage caused by the major storms from January to March of 2014 has totalized approximately 23 M€. Table 2.1 gives a general overview of the main socio-economic indicators of the Portuguese littoral. The length of the coastline subjected to erosion has increased to approximately 28% (APA, 2016). According to Coelho *et al.* (2009a) present-day shoreline evolution is to a large degree conditioned by the wave climate energy, the presence of numerous manmade structures and a progressive weakening of the alluvial sources (Figure 2.1).

Table 2.1. Overview of the socio-economic indicators of the coastal zones (APA, 2016).

Population (main urban and industry areas, important touristic areas and infrastructures)	75% (7.74 million inhabitants)
GDP (Gross Domestic Product) concentrated in the littoral	85%
Occupation with constructions (urban, touristic and industrial)	26%
Artificialized coastline	14%
Investment in defense infrastructures	High: 196 M€ (1995-2014)

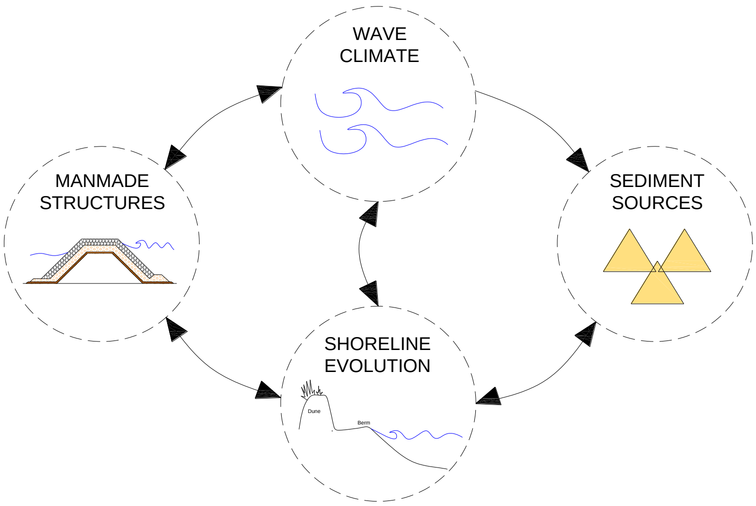


Figure 2.1. Shoreline evolution scheme.

Due to the coastal erosion problems, 14% of the Portuguese shoreline is protected by artificial structures, including groins, longitudinal revetments, breakwaters and harbor infrastructures, which adds up to around 140 km of the coast (APA, 2016). The wave conditions vary along the Portuguese coast, with changes in predominant wave direction and wave height statistical distribution from northwest to south coast. The northwest coast of Portugal corresponds mostly to low-lying open sandy beaches, backed by dunes (destroyed at some locations) and exposed to high-energy hydrodynamic forces, whereas the southern beaches, typically backed by high cliffs face less energetic wave conditions. These facts justify the large number of past coastal defense structures mostly implemented since the 1970’s, along the northwest coast of Portugal (see Figure 2.2). The first attempts of managers and stakeholders to cope with the erosion have essentially focused on maintaining the shoreline position with rocky structures (using *hard protection* methods) as way to deal with the high-energy wave power. Unfortunately, after decades, such short-lived interventions could not remove the problem but only treat the symptoms, influencing a variety of coastal features and damaging the natural landscapes and coastal ecosystems values. Against this backdrop, the last decades have witnessed a general increasing tendency to favor environmentally friendly coastal protection solutions through sand nourishments and reinforcement of dune systems projects. Since 1990, there has been a continuous increase in the number of artificial nourishments operations followed up by a sharp decrease in applications of hard engineering-based structures (see Figure 2.2). A similar pattern has been also identified by Hillyer (1996) when analyzing the interventions carried out by the US Army Corps of Engineers (USACE) in USA, between the 1950's and 1990's (Pinto *et al.*, 2018). Despite this trend has a national character, due to the higher touristic activity and low-energy wave conditions registered at the south region of Portugal, artificial nourishments have been mostly implemented to maintain beaches in Algarve, *e.g.* Rocha, Três Castelos, Alvor, Lacem, Tremoços, Quarteira, Vale do Lobo and Vilamoura beaches (Teixeira, 2011).

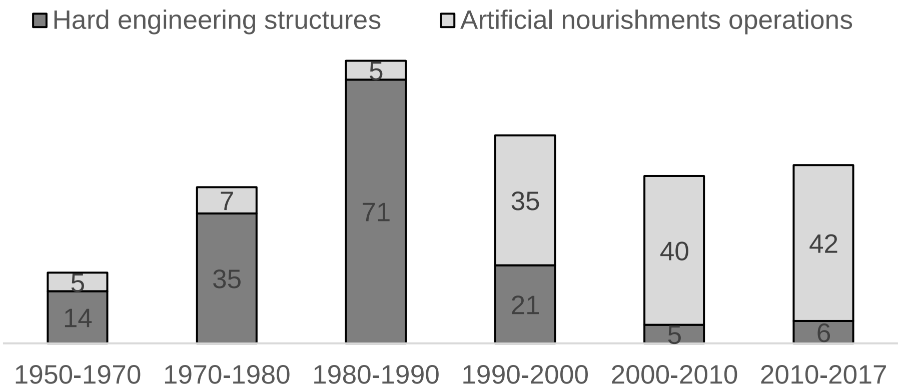


Figure 2.2. Number of coastal interventions in Portugal, since 1950 until 2017 (information based on Abecasis, 2014 and Pinto *et al.*, 2018).

From economic, cultural and environmental point of views, Portuguese coastal areas face multiple challenges and conflicts that demand a deep restructuration interfering with the coastal management policy, the functionality of the governmental services and the responses to the society/affected citizens (GTL, 2014). Figure 2.2 clearly evidences a recent paradigm shift regarding the coastal management policy, with the artificial nourishments becoming a favorite mean to mitigate erosion and maintain the coastline. Today's scenario differs from the one that has prevailed during 1950-1990, where the use of grey and heavy-based structures was a standard established by the Administration institutions and the technical-scientific community, and faced as the most efficient way to control the shoreline retreat, which already by that time had begun to threaten certain urban fronts. After the 1990's, the national scientific coastal community has started to identify patterns in the evolution of the littoral, which have highlighted some of the long-term negative effects associated with the hard-engineering solutions implemented to contain the erosion phenomenon (Pinto *et al.*, 2018). The increased erosion at the downdrift zone of structures like groins, seawalls and breakwaters, the narrowing/disappearance of the adjacent beaches, as well as the loss of the aesthetic and environmental values of the coastal zones came to point the need to establish sustainable solutions, falling into a *building with nature* approach (Pranzini and Williams, 2013; Pinto *et al.*, 2018). Artificial nourishments have then arisen as a high-potential alternative, passive to be applied in some locations, although their potential effects have not been well quantified yet. However, the past experience has shown that any action affecting coastal areas should look for a balance between coastal protection, enhancement of the land use and preservation of the environmental values. This implies necessarily some qualitative and quantitative understanding of the coastal morphological processes, as a precondition for a successful coastal management project, so all the parties concerned can be in position to understand not only the past, but also how the present situation has developed and how to anticipate future evolution tendencies. Management practices should then be based on solid knowledge, by identifying causes, recognizing past behaviors and intervening in favor of nature (Palalane, 2016).

The present chapter explores relevant issues related to the coastal evolution, planning and management in Portugal. The section gives a general overview of the recent morphological coastal development, summarizes some past interventions on coastal protection and identifies potential problems and challenges in order to assess the influence of different cross-cutting issues on coastal evolution. Special focus is given to the legal status and policy on coastal monitoring, by analyzing the administration responsibilities concerning coastal management, the instruments and schedules for field data collection. This chapter ends with a brief description of some of the future coastal protection measures that are part of a national coastal adaptation strategy proposed to fulfill a set of goals established until 2050. This strategy falls into a national program, initially undertaken for a deep reflection about the coastal zones aiming at the definition of a set of practical guidelines to reduce risks and promote the sustainable development of the littoral. A detailed description of the national proposal can be consulted in GTL (2014).

2.1. Coastal evolution: past vs present

Shoreline present configuration and position result from a continuous interaction process, between internal and external geodynamic and hydrodynamics agents, and more recently, the human-driven activities. In Portugal, the increasing anthropogenic pressure over the coastal zones has become, in many cases, incompatible with the natural dynamic, resulting in numerous situations of conflict between shoreline evolution, stakeholders and authorities. This interaction that shapes the shore on all spatial and temporal scales is extremely dynamic, turning any intervention policy and planning model, a very complex and longstanding task, which can only be achievable through the right understanding of the physics governing the coastal dynamic and its evolution.

When the evolution of the littoral is analyzed at the millennium scale (since the last maximum glacial, LMG, about 18 000 years ago), it is verified that the variation of the mean sea level (MSL) was the process that most conditioned the evolution of the shoreline position (GTL, 2014). However, the stabilization of the MSL that occurred 3 500 years ago (Dias *et al.*, 2000) has changed the dominant forcing. With the atmospheric circulation pattern without suffering any significant change (*i.e.*, with the wave regime maintaining reasonably invariant), the evolution of the littoral started to be mainly conditioned by the sediment sources. This means that, from that moment on, the sediment balance was the most important factor affecting the shoreline variation: an increase in the available sediments causing a seaward movement of the shoreline (accretion) and a sediment deficit resulting in a landward migration of the coastline (erosion). Overall, the exponential increase of the anthropogenic activities, in particular the deforestation and the agriculture, near the coast has contributed to a generalized accretion in estuaries and lagoons, having a very positive impact on the sediment sourcing (GTL, 2014).

Later in the XIX century, the littoral has started to present a regressive tendency evidenced by a shoreline retreat. This behavior is associated to the reduction of the sediment supply, mainly attributed to human-induced driving factors: construction of dams, sand extraction in the rivers and reservoirs, agricultural practices for soil conservation and construction of harbors (Coelho *et al.*, 2009a; Teixeira, 2014c). In Portugal, among all the potential causes, the damming activity is largely pointed out as the most determinant factor of the sediment deficit, being estimated that approximately 80% of the sediments that could be potentially transported in natural conditions are retained upstream (GTL, 2014).

Nowadays, the recognition of the relevance of the sediment balance in the shoreline evolution is of major importance to define strategic guidelines for coastal protection. The resolution of the problems associated to coastal erosion should attend to the main causes of the problem, which in the Portuguese case refers to the existence of sediment deficits. The management of the sediment budget should assume a central role in the development of any coastal defense strategy. A sedimentary cell is a concept that comes up in line with this thought. Faced as an independent unit, the definition of a cell allows the management of the coastal zones in accordance with sediment budgets. In each cell, the sediment budget is by definition the quantification of all the inputs (sources) and outputs (sinks) of sediments (Taveira-Pinto, 2004; EUrosion, 2006; GTL, 2014).

2.2. Geomorphology and sediment transport

According to the geomorphology and sediment dynamic, the Portuguese littoral is normally divided in 8 sedimentary cells (Figure 2.3): 1) Minho river - Nazaré; 2) Nazaré - Peniche; 3) Peniche – Cabo Raso; 4) Cabo Raso - Cabo Espichel; 5) Cabo Espichel - Sines; 6) Sines – Cabo São Vicente; 7) Cabo São Vicente - Olhos de Água e 8) Olhos de Água - Guadiana Mouth.

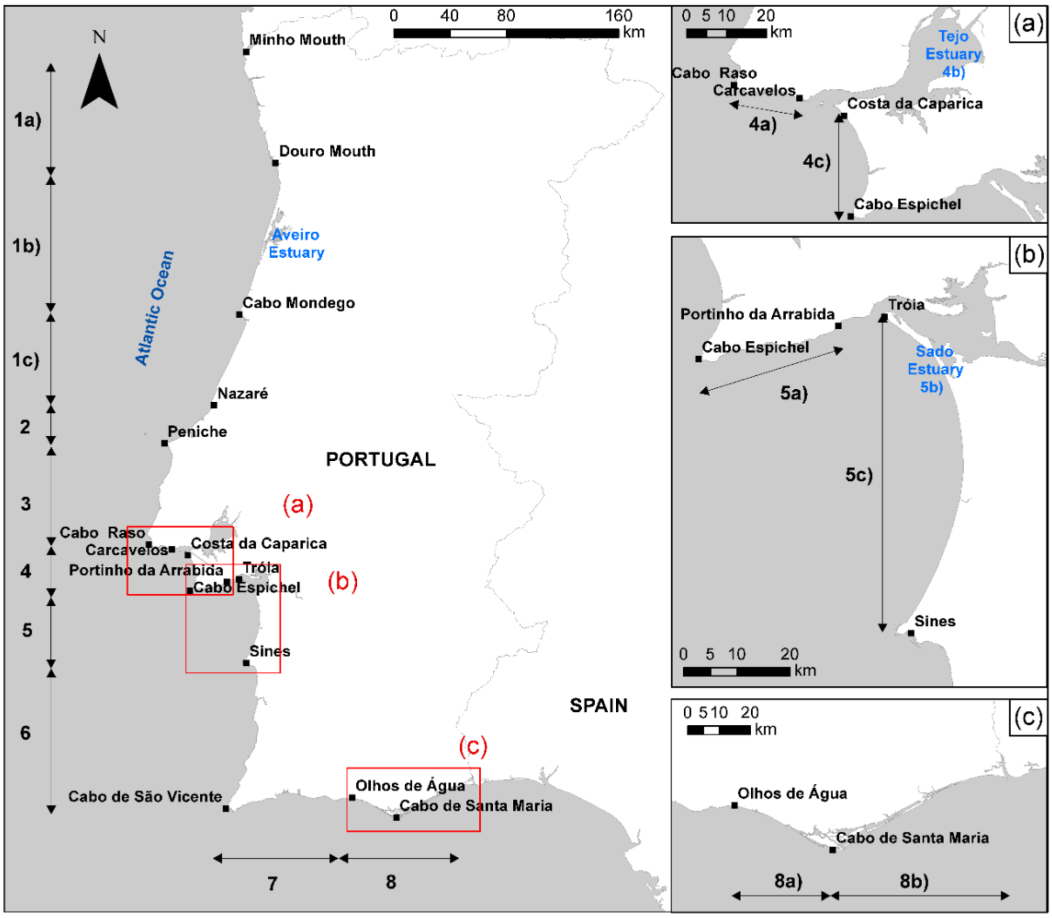


Figure 2.3. Geomorphology of the Portuguese littoral and corresponding partition in 8 distinct sedimentary cells (based on Santos *et al.*, 2017).

In order to better distinguish the coastal sectors dealing with discontinuities in the magnitude and direction of the sediment transport a subdivision of the cells 1, 4, 5 and 8 is here considered: 1a) Minho - Douro; 1b) Douro - Cabo Mondego; 1c) Cabo Mondego - Nazaré; 4a) Cabo Raso - Carcavelos; 4b) Estuarie of Tejo (including Caparica); 4c) Costa da Caparica - Cabo Espichel; 5a) Cabo Espichel - Portinho da Arrábida; 5b) Estuarie of Sado river; 5c) Troia - Sines; 8a) Olhos de Água - Cabo de Santa Maria; and 8b) Eastern segment of Ria Formosa.

The Table 2.2 presents a short inventory regarding the natural sediment supply process controlling the sediment budget in each cell. Beach morphology and sediment transport are briefly accounted, where alluvial sediment sources (inputs) are estimated in a past and current situation perspective (PS and CS, respectively), as well as the magnitude and direction of the potential and real littoral drift (Q_{POT} and Q_{REAL}, respectively) for each cell. PS is taken here as the prior situation to the existence of any anthropic perturbation interfering with the natural system (*e.g.* dams, coastal structures, harbors, artificial harbor channels, etc.) whereas the CS is admitted representative of the last two decades.

Table 2.2. Overview of the Portuguese littoral sectioned by 8 cells (GTL, 2014).

<table>
<tr><th rowspan="3">Cells</th><th colspan="3">Alluvial Sources</th><th rowspan="3">Q_{POT} [10^5 m^3/year]</th><th rowspan="3">Q_{REAL} (CS) [10^5 m^3/year]</th></tr>
<tr><th rowspan="2">River</th><th colspan="2">Volume [10^5 m^3/year]</th></tr>
<tr><th>PS</th><th>CS</th></tr>
<tr><td rowspan="13">1</td><td colspan="5">1a) Minho – Douro, NNW-SSE shoreline-oriented. Coarse and sandy beaches occurring in the dependence of the water courses backed by dunes. Rocky substrate.</td></tr>
<tr><td>Minho</td><td>1.4</td><td>0.3-1.2</td><td rowspan="4">10</td><td rowspan="4">1 (N-S)</td></tr>
<tr><td>Lima</td><td>0.2</td><td>0.07-0.1</td></tr>
<tr><td>Cávado</td><td>0.2</td><td>0.09-0.1</td></tr>
<tr><td>Ave</td><td>0.2</td><td>0.1</td></tr>
<tr><td colspan="5">1b) Douro – Cabo Mondego, NNE-SSW shoreline-oriented. Low-lying linear sandy beaches backed by dunes and cliffs (southern stretch of Quiaios). Retention of sediments in the Aveiro lagoon.</td></tr>
<tr><td>Douro</td><td>16.5-18</td><td>2</td><td rowspan="2">15-20</td><td rowspan="2">11 (N-S)</td></tr>
<tr><td>Vouga</td><td>0.3-0.4</td><td>0.3-0.4</td></tr>
<tr><td colspan="5">1c) Cabo Mondego – Nazaré, NNE-SSW shoreline-oriented. Low-lying sandy beaches. At south of São Pedro de Moel the shore turns into narrow sandy beaches backed by cliffs. Canyon of Nazaré act as a sink. Retention of sediments in the Estuary.</td></tr>
<tr><td>Mondego</td><td>0.4-0.8</td><td>0.4-0.8</td><td>15-20</td><td>11 (N-S)</td></tr>
<tr><td rowspan="3">2</td><td colspan="5">Nazaré – Peniche, NE-SW shoreline-oriented. Linear beaches (narrower at south) backed by cliffs. Rocky platform.</td></tr>
<tr><td>Western riversides</td><td>0.24</td><td>0.24</td><td rowspan="2">≅ 0</td><td rowspan="2">0</td></tr>
<tr><td>Tornada riverside</td><td>0.10</td><td>0.24</td></tr>
</table>

Table 2.2. Overview of the Portuguese littoral sectioned by 8 cells (GTL, 2014) – continuation.

<table>
<tr><td rowspan="3">3</td><td colspan="5">Peniche – Cabo Raso, N-S shoreline-oriented. Numerous sandy embedded beaches (diversified geometry). Wider and short beaches backed by a small dune system develop in the dependence of the watercourses while narrower and extensive beaches are associated to natural headlands.</td></tr>
<tr><td>Riversides (Peniche – Ponta da Lamporeira)</td><td>0.22-0.24</td><td>0.22-0.24</td><td rowspan="2">10</td><td rowspan="2">0.3 (N-S)</td></tr>
<tr><td>Riversides (Ponta da Lamporeira – Cabo Raso)</td><td>0.13-0.29</td><td>0.13-0.29</td></tr>
<tr><td rowspan="6">4</td><td colspan="5">4a) Cabo Raso – Carcavelos, WNW-ESSE shoreline-oriented. Small embedded beaches backed by cliffs.</td></tr>
<tr><td>Riversides</td><td>0.10</td><td>0.10</td><td>> Q_{REAL}</td><td>0.1 (N-S)</td></tr>
<tr><td colspan="5">4b) Estuary of Tejo (including Caparica) with seaward-directed concave shoreline. Southern stretch of the Tejo river is mostly formed by sandy beaches. At south of Bicas beach the littoral is backed by cliffs interrupted by short, coarse and sandy embedded beaches.</td></tr>
<tr><td>Tejo</td><td colspan="2">-</td><td colspan="2">$Q_{POT} > Q_{REAL}$</td></tr>
<tr><td colspan="5">4c) Costa da Caparica – Cabo Espichel, seaward-directed concave shoreline. Southern stretch of the Tejo river is mostly formed by sandy beaches. At south of Bicas beach the littoral is backed by cliffs interrupted by short, coarse and sandy embedded beaches.</td></tr>
<tr><td colspan="3">-</td><td>> Q_{REAL}</td><td>1.0×10^5 (S-N)</td></tr>
<tr><td rowspan="6">5</td><td colspan="5">5a) Cabo Espichel – Portinho da Arrábida, E-W shoreline-oriented. Littoral backed by high cliffs with small embedded beaches.</td></tr>
<tr><td colspan="3">-</td><td>0</td><td>0</td></tr>
<tr><td colspan="5">5b) Estuary of Sado river, with a seaward-directed concave shoreline. Sandy and continuous beaches backed by dunes (mostly at north of Medronheiro). Between Medronheiro and Melides, beaches are backed by cliffs.</td></tr>
<tr><td>Sado</td><td colspan="2">-</td><td colspan="2">$Q_{POT} = Q_{REAL}$</td></tr>
<tr><td colspan="5">5c) Troia – Sines, seaward-directed concave shoreline. Sandy and continuous beaches backed by dunes (mostly at north of Medronheiro). Between Medronheiro and Melides, beaches are backed by cliffs.</td></tr>
<tr><td colspan="3">-</td><td colspan="2">$Q_{POT} > Q_{REAL}$ (S-N)
$Q_{POT} = Q_{REAL}$ (N-S) – Melides beach southward</td></tr>
<tr><td rowspan="2">6</td><td colspan="5">Sines - Cabo de São Vicente, N-S shoreline-oriented. Numerous coarse and sandy beaches (typically narrow) backed by high cliffs or dunes (in the dependence of major rivers).</td></tr>
<tr><td>Mira</td><td>0.30</td><td>0.30</td><td colspan="2">$Q_{POT} > Q_{REAL}$</td></tr>
<tr><td rowspan="2">7</td><td colspan="5">Cabo de São Vicente - Olhos de Água, W-E shoreline-oriented. Morphology extremely diversified. Coastal stretches backed by cliffs alternate with beaches confined in headlands in the dependence to the rivers. Eastward of Lagos the littoral is extremely crenellated.</td></tr>
<tr><td colspan="3">-</td><td>> Q_{REAL}</td><td>0.01 (W-E)</td></tr>
<tr><td rowspan="4">8</td><td colspan="5">8a) Olhos de Água – Cabo de Santa Maria, W-E shoreline-oriented. Coastal stretch between Olhos de Água and Garrão corresponds mostly to a sandy beaches backed by cliffs.</td></tr>
<tr><td>Riverside of Quarteira</td><td>0.20</td><td>0.20</td><td>> Q_{REAL}</td><td>1.1 (W-E)</td></tr>
<tr><td colspan="5">8b) Eastern segment of Ria Formosa, SW-NE shoreline-oriented. System of island-barriers that separate the sea from the lagoon (Ria Formosa): 2 peninsulas and 5 island-barriers.</td></tr>
<tr><td colspan="3">-</td><td>> Q_{REAL}</td><td>1.0 (W-E)</td></tr>
</table>

Based on the inventory previously presented, important conclusions can be drawn about the past and recent coastal evolution in Portugal. The mainland Portuguese coastline presents a wide variety of geomorphological features, including amongst others extensive sandy beaches, dune ridges, lagoons, estuaries, cliffs, bays and barrier islands, which in turn shelter important coastal ecosystems from both ecological and biophysical points of view (Table 2.2). The coastline also hosts a large number of cultural heritage sites and urban seafronts, which in pair with an economic development induced by a general over-exploitation of the coastal resources has made numerous beaches increasingly vulnerable and exposed to erosion (Taveira-Pinto, 2004; Pranzini and William, 2013).

Poor sediment availability, mainly attributed to a general reduction of the feed capacity of the alluvial sources is one of the most important key factors contributing to a negative sediment budget (Table 2.2). Most of the sandy shores are suffering due to erosion, with retreat rates reaching meters per year. This is the reflection of what is happening in the northern sub-cells (1a, 1b and 1c, see Table 2.2), which besides the natural scarce of sediment input (mostly from Douro river), typically face high-energy waves and an intense longshore sediment drift, turning naturally the western continental coast the most vulnerable sector to erosion. This set of conditions explain how a continuous narrowing beach process has intensively developed during the past decades, forcing the implementation of numerous coastal defense structures, as well as emergency interventions for urgent repairs (Costa and Coelho, 2013).

2.3. Coastal protection interventions

The continental Atlantic coast of Portugal faces currently a scenario where beaches, dunes and cliffs have become one of the main sediment sources of the littoral drift. Simultaneously, the economic development and exploitation of the maritime industries has been increasing in response to the harbor’s needs, implying regular activities that also threat the coastal system. It is common knowledge that harbor breakwaters and coastal defense structures offer constraints to the natural shoreline evolution by conditioning the sediment transport and the available sediment volumes, having large impacts in the surrounding areas. As an attempt to maximize the benefit taken from maintenance activities of existing harbors, typically involving dredging operations or deepening activities of navigation channels, as well as to minimize negative impacts in the sediment budgets, port authorities have been adopting a new dredging management policy that combines the use of dredging and disposal activities on nearby sediment-starved beaches.

The harbor system of Continental Portugal is constituted by 9 commercial harbors: 5 main harbors (Leixões, Aveiro, Lisboa, Setúbal and Sines) and 4 secondary harbors (Viana do Castelo, Figueira da Foz, Portimão and Faro). Beyond the commercial value, in the jurisdiction area of these harbors, it is common to find fishing and nautical recreation activities, in some cases also with terminals for cruises. In addition to these harbors, along the Portuguese continental coast there are more than two dozens of fishing and recreation harbors (Vila Praia de Âncora, Esposende, Póvoa de Varzim, Vila do Conde, Nazaré, Peniche, Ericeira, Cascais, Oeiras, Baleeira, Lagos, Albufeira, Vilamoura, Quarteira, Olhão, Fuzeta, Santa Luzia, Tavira, Cabanas e Vila Real de Santo António, etc.). It is the economical and the social value of the harbors that justifies the performing of dredging operations. Its significance is evaluated by Portela (2011) in 63 million of tons of moving load per year, 130 thousands of discharged fish per year, 7000 sites of mooring of the nautical recreation and 300 thousands of passengers of cruises per year. Since 2006, according to the Portuguese Law 49/2006, 29th August, for any given dredging operation conducted within the littoral band limited by the line located 1km landward of the shoreline and sea boundary line of 1 mile measured from the shoreline (wherein the quality of the dredged sediments is considered suitable for deposition), the use of the dredged material for artificial nourishments is mandatory (Portela, 2011). Until then, the extraction and commercialization of the sediments in Portugal was allowed for different uses, removing sediments from the coastal system. It is therefore believed that this fact has contributed to the current sediment deficit in the littoral drift (GTL, 2014; Pinto *et al.*, 2018).

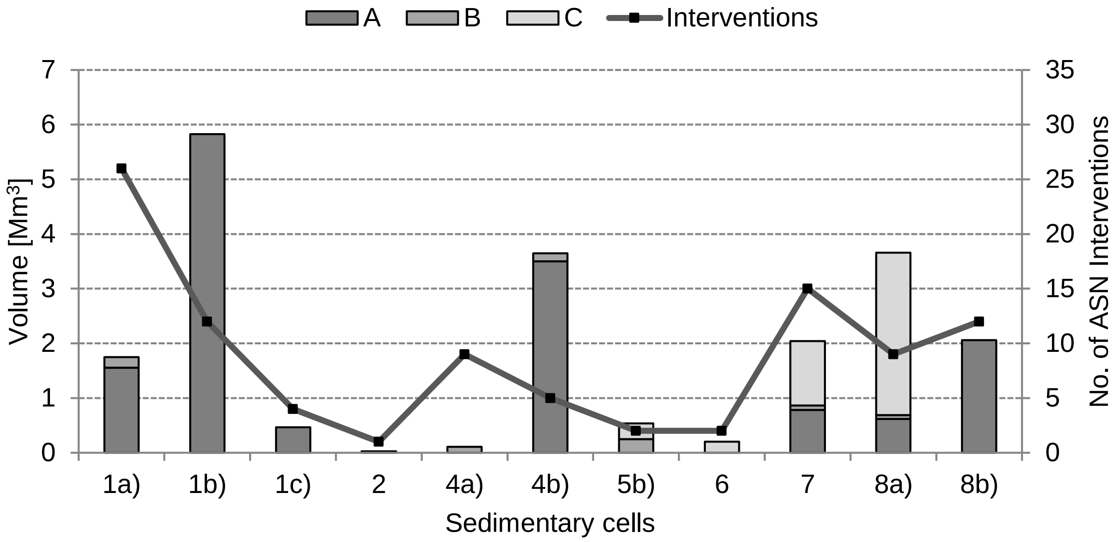
As previously stated, despite that numerous hard coastal engineering structures have been constructed since 1970's, during the last decades, such engineering solutions have given room to soft erosion mitigation strategies, where artificial nourishments play a central role (see Figure 2.2). As matter of fact, the biggest slice of the nourishment interventions has been undertaken in connection to regular harbor activities through the efficient use of the dredged material for sand replenishment of adjacent beaches (see a deeper analysis of the borrow sediment sources and disposal techniques in Chapter 3). This means that in the continental coast of Portugal, beach fill interventions derive mostly from the existence of "sediments of opportunity", resulting from dredging operations promoted by harbor-driven activities, fishing or nautical recreation. On the other hand, some of the most significant new hard-engineering interventions during the last two decades have been the groins implemented at the Areão and Poço da Cruz beaches (cell 1b), between 2002 and 2003, and the interventions performed in Espinho municipality (cell 1b), focusing on maintenance/reconfiguration operations of the groins field (which protect the main urban front) and longitudinal and cross-shore structures of Silvade and Paramos – cell 1b). However, all the existing coastal structures have been maintained and reinforced in a regular basis, as recommended by the main ruling coastal management tools.

Figure 2.4 gives a general overview of the spatial and temporal distribution of the artificial sand nourishments (ASN) operations that have been carried out along the Portuguese continental coast during the last two decades (1998-2017) by giving emphasis to three main indicators: 1) design purpose of the project (whether it aims at increasing the recreational value of the beach, combating erosion or both); 2) volume; and 3) number of interventions. The analysis exhibited in Figure 2.4 categorized as "artificial nourishment" any operation that has involved the deposition of sandy sediments (fine, medium or coarse) in the littoral band comprised between the bathymetric -10 m (Chart Datum, CD) and the 10 m (CD) elevation contour, including this way the subaqueous portion of the beach, the beach/berm and the seaward dune front. A detailed retrospective about the nourishment interventions performed in Portugal during 1950-2017 can be consulted in Pinto *et al.* (2018).

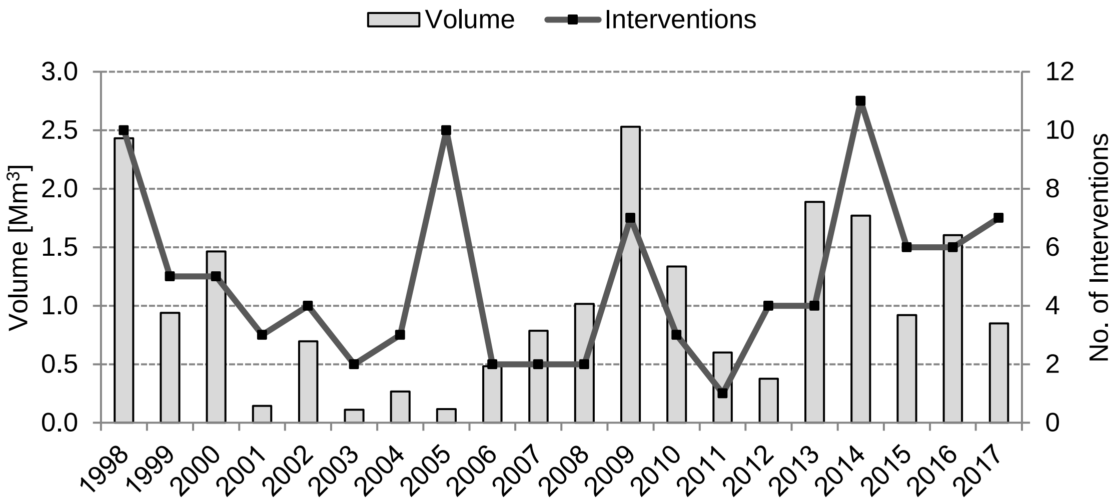
As can be observed from Figure 2.4, over the last two decades, more than 20 Mm^3 of sand have been used for sand replenishment purposes in eroding beaches, corresponding to 97 artificial nourishment operations/interventions in total. From this sum, there may be deduced an average deposition annual rate of approximately 1 Mm^3 per year.

In terms of spatial distribution, it is verified that the sedimentary cells 1b), 4b), 8a) and 8b) present the highest numbers of disposal volumes, revealing that a significant investment has been occurring in these cells. In contrast, only few nourishments interventions (less than 5) have been registered for cells 2, 4a), 6 and 1c), being all of lower magnitude (see Figure 2.4a).

With respect to the design purpose, it is deduced that along the northwest/west coast of Portugal the majority of the nourishments operations has been carried out with the ultimate goal to mitigate erosion risk (for example whether to control the shoreline retreat, protect hard-engineering structures or reduce coastal vulnerability and flooding), whereas for southern cells the enhancement of the recreational value of the beaches has been also a prime concern, especially for cells 7 and 8a).



a) Spatial distribution of the ASN as per each sedimentary cell. A, B and C represent the design purpose of the projects: A) Mitigation of erosion; B) Enhancement of the recreational value of the littoral; C) Both.



b) Temporal distribution of the ASN operations.

Figure 2.4. ASN interventions and volumes performed during the past two decades (1998-2017), based on Pinto *et al.* (2018).

It is here recognized the effort of the southern cells to maintain the recreational use of the beaches through the increase of the beach width (and consequently the carrying capacity of the beach) and the protection of the natural resources, whereas the biggest concern of the northern cells have mostly focused on coastal protection for means of shoreline stabilization. This is in part due to the favorable wave environment and local morphology found at the south, which theoretically would provide the optimal conditions to best benefit the retention process of the nourished sand and subsequent longevity of the intervention.

The municipalities with the highest deposition volumes were Ílhavo (Aveiro), Almada (Setúbal) and Loulé (Faro), which fall into the cells 1b), 4b) and 8a), respectively. The nourishment activities carried out in these municipalities represent almost 60% of the total fill volume deposited during the last two decades, being Ílhavo the most nourished municipality (fill volume about 5.4 Mm^3, 27%).

Overall, despite its non-linear temporal distribution it is possible to confirm that there has been an increasing investment (in number and volume) over time with Portuguese artificial nourishments operations (see Figure 2.4). The years that have registered the highest number of interventions correspond to 1998, 2005 and 2014 with 10, 10 and 11 operations, respectively, whilst the major dumping volumes has been recorded in 1998, 2009 and 2013 with approximately 2.4, 2.5 and 1.9 Mm^3 of sand, respectively.

Although the potential use of dredged material for sediment replacement of eroding beaches has been highly recognized since 2006, contributing to the maintenance of beaches that have become depleted of material, the environmental impacts resulted from such operations have been poorly quantified. Solutions combining dredging/disposal activities are expected to induce changes in the beach morphology and generate unexpected impacts in the environment. For this reason, identification and sharing good practices for coastal management is of major importance. Unfortunately, there is still little comprehensive guidance available for engineers or planners regarding an integrated coastal management approach.

2.4. Vulnerability and risk of the Portuguese coastal areas

Along the Portuguese coast, especially in the north, there are several dune ridges in fragile condition and suffering from extensive degradation. This is mainly a consequence of urbanization along the coast that has proceeded for decades near or over dune fields, without any consideration about their significant benefits for the environment (Taveira-Pinto, 2004). The following paragraphs describe briefly the vulnerability of Portugal’s main coastal stretches to flooding and erosion risk, according to the areas territorially affected by each Administrative Hydrographic Regions (ARH), by giving special attention to 2014's storms events (Hércules and Stephanie) as examples of typical storm-induced impacts on the coast (APA, 2014).

The coastal area affected in the North ARH develops along an estimated length of 144 km, from the mouth of the Minho Estuarie until the municipal north boundary of Esmoriz. The areas with higher level of vulnerability to erosion and overtopping/flooding, and consequently under high risk, are located near the seafronts of Moledo do Minho, Amorosa to Castelo do Neiva, São Bartolomeu do Mar, Ofir, Apúlia, Aguçadoura, Árvore to Mindelo, and Granja to Paramos (Veloso-Gomes, 2007; APA, 2014).

In January and February of 2014, in the sequence of erosive and overtopping/flooding events associated to the Hércules and Stephanie storms (APA, 2014), it was registered numerous occurrences in different places (*e.g.* Moledo, V.P. de Âncora, Castelo do Neiva, Belinho, Mar, Ofir, Pedrinhas/Apúlia, Cedovém, Estela, Mindelo, Angeiras, Lavadores/Salgueiros, Salgueiros/Madalena, Madalena/Francelos, and Francelos/Miramar), reporting several damages in beach access walkways, dune systems, beach equipment/supports and coastal protection/defense infrastructures.

The area of intervention of the Center ARH is located between Esmoriz and the southern boundary of the Vieira Beach and is approximately 135 km long. This is the coastal stretch with the highest erosion rate, with shoreline retreats records around 200-300 m over the last 50 years (Lira *et al.*, 2016; Santos *et al.*, 2017). The shoreline retreat rates, in this coastal stretch, reach in some places 7 m/year (APA, 2015). The areas of highest vulnerability are located in Esmoriz/Cortegaça, Maceda, Furadouro, Barra, Costa Nova, Vagueira, Cova-Gala, Lavos, Leirosa e Pedrogão.

The previous referred storms had also a significant impact on this stretch, being the most affected municipalities: Ovar, Ílhavo, Figueira da Foz and Leiria. These storms have contributed to a significant retreat of the dune system downdrift of the existing groins and longitudinal revetments (maximum of 40/50 m), producing substantial structural damages on the later.

The coastal stretch between the Vieira beach and Cabo Espichel is referred to as Tejo and West ARH, corresponding to 260 km of coast. The area under highest risk is located between Sao João and Costa da Caparica, and has retreated more than 200 m in the last 50 years (Pinto *et al.*, 2008; Silva *et al.*, 2013). Also, it is extremely often subjected to the occurrence of erosive episodes and overtopping/flooding of the dune system (São João) and over the revetment/walkway marginal (urban zone) during storm conditions (*e.g.*, 2007, 2008, 2010, 2014). The storms of January and February 2014 had also a negative impact along this stretch, resulting in several damages to the municipalities of Marinha Grande, Alcobaça, Mafra, Sintra, Cascais and Almada.

The fourth coastal stretch with 215 km of extension is under the administration of the Alentejo ARH and is located between Cabo Espichel and Odeceixe beach. The highest risk situations arise from the evolution of cliffs contiguous to areas with an intense human occupation, in Arrábida and at south of Sines. Between 1937 and 1957 and in 2012, 161 mass movements were inventoried by photointerpretation, which produced crest retreats ranging from 3 to 25 m (NEMUS, 2015). Carvalhal, Santo André, Fonte do Cortiço, São Torpes, Morgavel and Zambujeira do Mar were the municipalities that felt the most negative impacts from the storms of 2014, involving very serious events with overtopping and also flooding.

The last coastal stretch is the Algarve ARH and extends from Odeceixe beach to the Mouth Guadiana river, comprising 270 km of coast. High risk situations (in littoral of rocky cliffs) result from occurrence of irregular and discontinuities of mass movements of different types and dimensions at the base and at the top of cliffs in front of urban areas. Between 1995 and 2014, 244 mass movements were observed, which have contributed to retreats ranging from 1 to 20 m (Teixeira, 2014a). In littorals of soft cliffs, having linear and parallel retreats, the erosion occurring between the 1970's and 1990's (retreat between 50 and 100 m in some locations) constitute the main factor of risk to the seafronts located at the top, where two houses have been demolished in 2004 (Teixeira, 2014a). In low-lying and sandy littorals, the highest risk is associated with erosion and overtopping/flooding mechanisms, already observed in some locations of island-barriers with an intense human occupation (*e.g.* Faro beach, Fuzeta, Armora) and processes related to the dynamic of tide-bars. In early 2010, the overtopping events and the natural opening of a new tide bar in the Fuzeta Island have caused the destruction of 44 houses (Teixeira, 2014b). In Faro beach, numerous overtopping events have also affected parking zones, the main road and different housings. The storms Hércules and Stephane have also caused several damages in walkways near the beaches of Armação de Pêra, Vale Olival, Carvoeiro and Vale Centianes as well as some beach equipments in Beliche and Tonel beaches (APA, 2014).

Beyond the growing intensity of the risk linked to coastal flooding and erosion, other environmental problems to solve are related with chronic pollution (often observed in coastal areas close to factories and industries) and punctual pollution (linked to beach oiling). Since in both cases the problems are connected to human settlements along the coast, either directly by the pressure induced on natural areas, or indirectly by the impact caused by economic activities, it is expected that priority should be given to spatial planning in the framework of coastal erosion hazards, risk mapping and environmental assessment (Taveira-Pinto, 2004).

2.5. Coastal management and planning

Since the very beginning, in Portugal, political attention was given to the coastal zones, resulting in the creation of specific legislation and administrative entities with coastal management responsibilities. Also, the need for a better management of the coastal zones has led to several political commitment measures and policies to improve relations between human activities and the coastal environment. This situation has resulted in specific legislation and national strategies, regional management plans, studies and research. The coastal management is built on a significant number of Decree-Laws and instruments that, if applied, should help to protect coastal environments more efficiently. Although, the existing legislation and instruments are quite complete, they are not as effective as they should be, in part due to the lack of coordination between the parties involved. The complex relationships between human activities and the coastal environment are sometimes neglected, and some measures often fail to achieve their goal or may even be contradictory (EUrosion, 2006).

2.5.1. Administration, legislation and regulation

In Portugal, coastal waters and beaches are considered maritime public domain and state-owned. There are numerous public institutions (from national to local levels) that somehow interfere with the coastal zone, which sometimes can lead to important difficulties such as overlapping or vagueness of responsibility. Over the years, the Portuguese administrative system has been suffering from several processes of restructuration, with some Ministries being created (Ministry of Planning and Infrastructures), splitted up (Ministry of Environment and Ministry of Sea) and/or merged to others (Ministry of Agriculture, Forests and Rural Development). Although there are several institutions responsible for the coastal zones, nowadays, the prime legal authority is the Ministry of Sea. This Ministry has the mission of coordinate all subjects related to the sea, by defining and monitoring the National Strategy for the Sea, promoting the scientific knowledge, the innovation and the technological development in the maritime domain. This Ministry also defines and coordinates all the policies of coastal protection, planning, management and exploitation of the coastal resources, in order to promote a sustainable economy and use of the sea. The licensing and surveillance of the fisheries, the promotion of work in harbors and navigation channels and the management of the national European funding related to the sea is also supervised by this sector of the government (RP, 2018). Institutions like Portuguese Environment Agency (APA), and Institute of Nature Conservation and Forests (ICNF) have jurisdiction over all coastal zones except the areas of harbor jurisdiction that are controlled by the Harbor Administrations (HA's) and supervised by APA.

During the last decades, the management of the Portuguese coastal areas has been conducted by a complex legal and institutional network. The current Portuguese legislation applicable to the coastal zones is built upon several Decree-Laws from different periods and with a variety of scopes, sometimes with overlapping contents and without a clear connection between them.

2.5.2. Policy tools for coastal zone management

Territorial management is in a general way the supervision of territorial planning procedures. According to the Portuguese Decree-Law 380/1999, 22nd September, the planning process is conceived as a sequence of procedures, with different plans at each level of decision-making, having different approaches, principles and goals, all subordinated to the highest plans in the hierarchy. Thus, the Portuguese planning system is divided into three main levels of decision-making: national, regional and municipal (Taveira-Pinto, 2004), where the application of multiple principles or measures often leads to a distribution of responsibilities between these competence levels (EUrosion, 2006). The aim of such plans is to ensure the correct use and organization of the national territory in order to achieve an integrated social, economic and cultural development for different regions and urban areas. Portugal operates in a highly centralized way which implies that in practice, with the municipalities having relatively limited responsibilities. Table 2.3 presents a summary of the existing policies and hierarchy scheme between them.

Table 2.3. Planning tools (Taveira-Pinto, 2004; EUrosion, 2006).

Coastal Zone Management Plans (POOC)	Regional Plans	Municipal Plans
Regulatory planning tool, elaborated by the Government; Establishes different uses and specific activities to be developed along the coast; Classifies beaches to be developed along the coast; Classifies beaches and regulates bathing use; Coordinates coastal development and resource conservation, ensuring public access to the coast; Regulates nature conservation and shore protection.	Implements at a regional level, the options and guidelines of National Management Territory Programme, and the Sector Plans; Translate, in spatial terms, the main objectives of economic and social sustainable development of the Regional Development Plan, minimizing ecological loading; Take measures that can lead to the reduction of intraregional development inequalities; Regulates territorial development. Under this plan, other special and municipal plans have to be implemented; Defines a model for regional territory organization.	Regulatory planning tool, approved by the municipalities; Establish the land use management by zoning, propose models of human occupation, urban and transport organization, physical infrastructures location and parameters of land use and environmental quality; Establishes the (charge) capacity of the territory; Support the social and economic development policy.
Note: Coastal Zone Management Plans (POOC) were in 2015 officially replaced by the Coastal Management Programs - POC (see Section 2.5.3)		

2.5.3. Management plans for the Portuguese coastal zones

The Portuguese coastal management plans represent, at the regional level, management procedures to enhance quality and sustainable use of coastal resources, being the first step towards such goals. These plans are one essential instrument to develop management approaches capable of correcting and preventing coastal conflicts. In a very recent past, continental Portugal was divided into nine coastal stretches, each one having an individual coastal zone management plan (POOC). These plans were comprised between: Caminha - Espinho, Ovar - Marinha Grande, Alcobaça - Mafra, Cidadela - S. Julião da Barra, Sintra - Sado, Sado - Sines, Sines - Burgau, Burgau - Vilamoura and Vilamoura - Vila Real de Santo António. This partition was made by taking into account singular and similar features of each area as well as territorial administrative boundaries. The aim of these plans was to provide the basis for spatial and land use planning of coastal zones, beach management, sustainable tourism development, regulation of coastal waters and nature conservation. However, due to the most recent restructuration of the legal state-framework in terms of territorial planning and urbanism (Law 31/2014, 30th May; Decree-Law 80/2015, 14th May), the ruling coastal management plans (POOC) gave rise to new five management tools, namely Coastal Management Programs (POC), each one corresponding to a specific management unit by Administrative Hydrographic Region (see Table 2.4, APA, 2018).

Table 2.4. POC's, the new management tools (APA, 2018).

Administrative Hydrographic Region	Coastal Management Program (POC)
North	Caminha – Espinho
Center	Ovar – Marinha Grande
Tejo and West	Alcobaça – Espichel
Alentejo	Espichel – Odeceixe
Algarve	Odeceixe – Vilamoura
	Vilamoura - Vila Real de Santo António (POOC)

Although these new programs are still in a large stage of development (with the exception of the POC Ovar - Marinha Grande, which has been already approved by the Resolution of the Ministry Council no. 112/2017, 10 August), they maintain the national character. However, assuming a more pragmatic and strategic scope, by establishing exclusive regimes that safeguard resources and natural values through principles and management standards/rules (APA, 2018). These programs are directed only to the public entities and maintain its dominance over the inter-municipal and municipal territorial. This has raised a new paradigm around the territorial management instruments, where the territorial management tools addressing municipalities' responsibilities are the only ones directed to the private entities. The administrative entities now face a challenge, at a national, regional and local level, regarding an adequate coordination, deliberation and concertation of all the interests involved, to decrease the level of risk of the most vulnerable zones of the Portuguese littoral, so the development of the activities most dependent on the sea proximity can be ensured (GTL, 2014).

2.5.4. Coastal protection and decision-making process

As coastal management is mainly dealt with at national level, the general practice is that there is no funding from private organizations for coastal protection, being the costs almost exclusively borne by public funds, either municipal, national or EU Commission funds (70% to 100%). The administrative process of decision-making has already been stated and it is associated to the jurisdiction on coastal areas. However, in terms of coastal erosion, the main responsibility lies with APA, which has the commitment to provide the correct technical support and measures to mitigate erosion problems in the near future and after severe storms events. APA is responsible for issuing permits for coastal protection and other structures in the coastal zones, requiring anticipated studies of eventual environmental related-impact to the coastal zones. Stakeholder involvement is allowed by law in every part of the environmental impact assessment process. However, the common practice is for low participation in the consultation process unless there are specific interests to be safeguarded (Taveira-Pinto, 2004). Although this involvement has, so far, been very limited, it should be encouraged because of the significant added value it would give to the decision-making.

2.6. Monitoring at an institutional and public level

The coastal zones are very complex areas comprising simultaneously the maritime and terrestrial domain, with multiple dynamic processes that change the coastal morphology at all time and space scales. Given the intensity and the magnitude of these changes, the implementation of procedures and tools based on reliable data, able to improve the knowledge and support the coastal management is of major importance. Any coastal policy that is well clarified, rational and realistic requires the access to high-quality data sets, so they can be used for different purposes and domains as a way to help finding sustainable solutions for different contexts (GTL, 2014).

The access to data generally results from two main processes that converge to the same purposes: 1) Data from information systems (IS), geoportals or platforms, based on internet systems that organize the contents and services supported by the data, such as, searching and consulting tools, resources of support and processing and also applications supported by data catalogues; and 2) Data resulting from monitoring campaigns undertaken *in situ*.

2.6.1. Special data storage infrastructure (SDSI): gaps and good practices

All the coastal data and information should be integrated in a special data storage infrastructure (SDSI) – here the information about the location, typology, formats, scales, the geographic and temporal context of the data acquisition, as well as, who have it and how the data has been collected are essential for a correct use.

England offers an example that is considered a very good practice in terms of monitoring procedures supported by an information system. The *Channel Coastal Observatory*, is an online platform for coastal management that combines and makes available sets of data collected through regional and strategic monitoring plans of the coastal zones. The idea behind this platform, presented by a group of researchers to the British government, firstly to overcome some coastal problems in the south of England, is to create a solid scientific basis by facilitating the general access to important information for support studies and research projects.

Through this system, any researcher, technician or citizen has access to the information of interest for different purposes of analysis and intervention in the coastal zones. The information available in *Channel Coastal Observatory* involves several geographic and temporal series of photography, LIDAR, topographic and hydrographic data, aerophotogrammetry, sea bottom maps, waves and buoy data, sediment distribution maps, controlling GPS points, models and physiographic lines.

Portugal, in general, holds the same kind of data available as those at *Channel Coastal Observatory*, although they differ significantly at the temporal and spatial coverage level, being less systematic and comprehensive, respectively. In some cases, the information is handled following a negligent coordination, without a systematic and adjusted acquisition system (Pranzini and William, 2013; GTL, 2014). Also, the fact that there is no centralized access to the data, with the information dispersed in different institutions (having different policies of data assignment and access), defines one of the major limitations faced by the Portuguese infrastructure database. There are several Portuguese institutions that have been collecting data relevant for coastal management: Hydrographic Institute (IH); General Directorate of the Territory (DGT); APA; General Direction of the Natural Resources, Security and Maritime Services (DGRM); Geographic Institute of the Army (IGeoE); National Institute of Statistics (INE); Institute of the Conservation of the Nature and Forests (ICNF); Harbor Administrations (HA’s); Portuguese Institute of the Sea and Atmosphere (IPMA); General Direction of the Sea Policy (DGPM); General Direction of the Maritime Authority (DGAM); Laboratory of Energy and Geology (LNEG); Laboratory of Civil Engineering (LNEC); Commissions of Coordination and Regional Development (CCDR); Universities; Research Centers and Municipalities.

From all of these public institutions, very few adopt a policy of open data. The majority follows different existing policies of data assignment and access, different administrative services, sometimes with access restrictions to the data, requiring in some cases payment for data access.

2.6.2. Portuguese information systems infrastructures

Considering the national-framework sector that currently focuses on the geographic information and the coastal zones in particular, it is possible to conclude, to a large or lower degree, that there is a lack of updated and systematic information of the decision-making at present. However, these shortcomings recognized for the geographic data are not an exclusive problem of the coastal zones, reflecting also difficulties in the data policy at a national level (Santos *et al.*, 2017).

The National Geographic Information System (SNIG) is the Portuguese infrastructure managed by the General Directorate of the Territory that allows public and private Portuguese entities to share the geographic information that they produce. However, the geographic data is not made available in its pure form, instead, the infrastructure only provide, from different points of access, a set of metadata and geographic services produced or maintained by public and private entities. Realizing these restrictions, it is easy to infer the numerous difficulties faced by users when accessing the geographic data. The strategic importance of the data held by the public institutions is highly recognized by the modern society. For this reason, this issue should mainly be dealt with at a national level, especially when the data is useful to support the definition of public policies, as it is the case of the integrated and sustainable coastal zones management policy (GTL, 2014).

Ideally, a good SDSI should have a national character and be fed by geographic data acquired in a systematic way, available to everyone and whenever possible based on interinstitutional partnerships. Such SDSI should congregate efforts that could allow strategic cooperation promoting an adequate data collection policy for creation of a wide and systematic repository of knowledge. Unfortunately, this requires a large political commitment and only a few existing systems can be pointed out as good examples, for instance, the infrastructure of national special data of the United States. This infrastructure, considered a worldwide reference in the monitoring domain, was strongly encouraged by the government (Clinton and Bush Administrations), with the final purpose to create a transverse, solid and wide database system. As this information is paid with taxpayers' money it is by definition considered totally public and everyone can have access to it. The basis of any program involves a large number of partnerships as the one that supports the American program Digital Coast/NOAA (GTL, 2014).

It is important to emphasize that the geographic data are not the only relevant data for the knowledge of the coastal zones. There are other types of data that matter, although also dispersed into different entities, creating the risk of information being lost or extinguished in the absence of a national monitoring plan. In line with that, the integrated and sustainable management of the coastal zones is being articulated with the sea policy. A new information system is currently under development, the SNIMar geoportal – *Integrated Geographic Information for the management of the marine and coastal waters* – which aims to create a marine spatial data infrastructure that addresses the issues "what data on the marine environment exist?", "where are those data?" and "how to access it?" (SNIMar, 2018). This project intends to gather information, which is totally or partially related to the marine environment and that is currently scattered over several public and private entities. This may consist of different types of information falling into the distinct disciplines: bathymetry and geomorphology; biodiversity and conservation, biotechnology, energy and geological resources, geophysics, geology, infrastructures, human activities, fishery and aquaculture, nautical tourism and sports; legal limits, meteorology, monitoring and environment quality control, navigation traffic and safety, earth observation, oceanography, management and spatial planning, cultural heritage and pollution. The idea is to standardize and display all of this information through an accessible and user-friendly technological platform - a geoportal, by integrating not only recent information, but also historical records related to the Portuguese marine environment. This web interface would enhance public access to important information related to the marine and coastal areas, being a key tool for the environmental management of the Portuguese marine waters and contributing to the implementation of the Marine Strategy Framework Directive (MSFD), since it will simplify the sharing, searching and accessing to metadata and marine data, particularly useful for public administration, universities and research institutes (SNIMar, 2018). The SNIMar geoportal will also be the marine data branch of the National Geographic Information System (SNIG). In turn, SNIG is articulated under the INSPIRE Directive, with a European spatial data infrastructure that supports the decision-making of community environmental policies and other policies or activities which may have an impact on the environment (SNIMar, 2018).

Also, the Administration System of the Littoral Resources (SIARL), released in 2011 and currently integrated into the DGT, is articulated under the INSPIRE Directive. The SIARL was originally developed with a primary goal to facilitate the access to the collective existing knowledge about the littoral and support decision-making processes in line with a sustainable development policy. The concept provides access to the information to everyone that is interested in getting into the coastal issues, where it is possible to converge and link the technical and scientific knowledge of different disciplines with the needs of the technicians and decision-makers representing different areas and with areas accessible to citizens (Santos *et al.*, 2017). Although, the SIARL was considered a promising, versatile and suitable tool in terms of data sharing, much of its potential has been wasted, at least as a repository of coastal data and as a collaborative platform intended to contribute to an integrated and sustainable management policy of the continental coastal zones. The major weakness of this system is related to the frequent changes occurring at the institutional level, with permanent changes of procedures, which are not compatible with bureaucracies that this kind of systems requires, especially for platforms with a collaborative character as the SIARL.

With the natural dissolution and merging processes resulting from recurrent restructuring of the legal-state framework, as well as in a context of a serious budget constraint, the SIARL ended up being integrated into an entity without any vocation or competences for the management of the coastal zones, thus, losing the most important partners linked to the project and very interested in coastal management (GTL, 2014).

2.6.3. Portuguese monitoring priorities

According to the legislative order no.6574/2014 of the Environment Secretary Office of the State of the previous Ministry of the Environment, Territory Planning and Energy of 12th May 2014, the current themes considered as a state-priority in terms of monitoring of the Portuguese littoral are: 1) the sediments dynamic and any external factors inducing changes on it; 2) the coastal interventions in order to better understand their physical behavior and their impact on the coastal system to optimize the associated lifetime and corresponding investments; 3) the marine and coastal biology to avoid possible conflicts and impacts resulting from coastal interventions, deserving also particular attention to the continuous update of the sea bottom; 4) events that can induce physical damages and material losses in the littoral, including causes and effects (of an oceanographic or climatological nature, etc.); and 5) the land use and activities (for terrestrial and maritime domain).

Such monitoring procedures will allow to: 1) map the risk and vulnerability along the coast; 2) determine coastal sediment budgets; 3) analyze shoreline evolution; 4) define and characterize the land use and activities; 5) update and adjust the coastal management tools; 6) update the constraints faced by the system; 7) obtain relevant information for developing cost-benefit analyses; 8) establish indicators of risk and evolution allowing a quick analysis and diagnostic of the ongoing situation and registered evolution; and 9) create important databases and information systems aiding the decision-making process.

Most of this information requires specific surveys, but an important portion can be extracted from the geographic information which is crucial for several sectors. A data acquisition policy based in a planning that congregates different interests from various sectors is fundamental to converge efforts, although a larger number of partnerships and political commitment is required.

2.6.4. Monitoring program of the Portuguese coastal zones (COSMO)

Monitoring practices assume a strategic character for the country, appearing consistently as one of the main recommendations for a sustainable and integrated coastal zone management (GTL, 2014; GTS, 2015). The monitoring offers a solid technical and scientific basis that is considered fundamental for a well-supported planning and management of the coastal zones (including the new POC’s and coastal defense interventions), contributing also for a greater rationality and sustainability of the solutions adopted by the decision-makers. The entities in charge of the coastal zones, in which APA assumes a central role, recognize increasingly the need for a better integration of the existing knowledge about the dynamics and evolution of the coastal system into the territorial management plans in order to ensure a proper balance between the use of the water resources and the mitigation of the associated risks for human beings and seafronts. Although, the integration of this knowledge is generally seen as a key factor into the processes of management and decision related to the coastal zones, it has still been handled in a casuistic and sparse way, following predominantly a “reactive” rather than “preventive” policy. This situation has mainly developed due to the absence of systematic monitoring data in connection to the coastal evolution of the littoral (*e.g.* shoreline position, seasonal morphological changes, cross-shore material exchange between the subaqueous and subaerial portions, storm-induced beach changes, dune and cliff erosion scarf, etc.) as well as to the inexistence of an operational and strategic monitoring program for the entire Portuguese continental coast.

In 2016, a Monitoring Program for the Portuguese Continental Coast, known as COSMO, estimating an investment of 3.1 M€ over three operational years and focusing on 161 beaches along 243 km of the coast (encompassing 92% of the coastal municipalities, 46 counties) was proposed. Due to delays, resulting from the project adjudication procedure, this national program, approved by the Ministry of Environment in January of 2017 and with plans to start in the same year, still continues in standby, waiting for a new rescheduling. This program, mainly developed to mitigate the coastal risk and support the coastal management and the decision-making, establishes a set of measures and guidelines for data collection, processing and analysis that can be used as diagnostic indicators of the coastal zones. The monitoring will be carried out through establishment of cross-shore beach profiles (in annual/semiannual basis), surveyed from an alongshore base line located at the beach to a bed level -20 m, subaqueous profiles (quarterly basis), integral surveys to the beaches (semiannual to annual basis) and cliffs (initial and final) and topo-hydropathic surveys to specific areas (annual to biannual basis). Data acquisition will involve innovative techniques of data acquisition, namely, photogrammetry and LIDAR. According to the project, attention will be given to the certain coastal features (COSMO, 2016):

1) width and height of the dune system (when applicable);
2) width and volume of the dry portion of the beach;
3) morphology and volume of the subaqueous portion of the profile (limited by the depth of closure);
4) shoreline position (from an alongshore baseline located at the dune foot);
5) width and volume of the instabilities (*i.e.* mass movements) in the cliffs (when applicable);
6) position of the top of the cliff (when applicable).

The spatial and temporal resolution of the monitoring campaigns as well the typology of the operations were established by taking into account not only a wide set of factors (morphodynamic, vulnerability, occupation and presence of coastal defense structures) as a function of the level of the risk observed in the past and updated knowledge about the evolution tendencies of the coastal zones, but also the recommendations given in the

Action Plan and Valorization of the Littoral 2012-2015 by APA, the GTL (2014), GTS (2015) and the ongoing POC's.

This monitoring data will be also useful to support research studies, define the trigger for certain management interventions, anticipate problems and determine the type of project and timing of engineering structures. The data collection will objectively contribute to (COSMO, 2016):

1) understand the past: determine long-term tendencies is fundamental to better understand the natural evolution of the beach;
2) identify the current problems of the shoreline (sandy shores or cliffs);
3) stepping the management interventions and/or protection interventions;
4) calibration and validation of coastal numerical models: improve numerical model predictability;
5) evaluation of the success level and general behavior of any engineering intervention;
6) access to the impact of interventions on the coastal system;
7) provide evidences that the project (*e.g.* intervention) fulfilled the proposed requirements.

The coordination and implementation of the national program COSMO will be supervised by the Department of Littoral and Coastal Protection of the APA. The inspection of this program, due to its technical and specialized character, will be ensured by one or more investigation units, constituting this way a baseline for other research projects (COSMO, 2016).

2.7. Data collection approaches

The only way to make management practices accountable, *i.e.*, with optimized costs against values at risk, is to learn how to study and apply sustainable coastal engineering techniques. Along the years, systematic monitoring and data collection have been the typical challenges faced by coastal practitioners. In Portugal, when it comes to produce data, large amounts of funding are required and difficult to get, justifying why such information are rare and mostly available for major projects. Coastal practitioners and researchers have to be provided with some qualitative and quantitative understanding of beach change morphology in order to better support the decision-making process.

Generally speaking, there are three main approaches that can be used to obtain data for studying beach morphology change and the underlying physical processes: laboratory experiments using small wave tanks (generating wave heights on the order of magnitude of 0.1 m), experiments employing large wave tanks (involving wave heights on the order of 1 m), and field measurements.

2.7.1. Laboratory approach

Numerous laboratory studies of beach profile change have been performed with small wave tanks. Such experiments have proven valuable for identifying potential parameters controlling beach change and qualitatively describing profile features. However, as demonstrated in a landmark paper by Saville (1957), in which profile change generated in small and large wave tanks was compared, a considerable scale effect is introduced through the magnitude of the wave height. Other independent variables may also produce a scaling distortion, and generally applicable scaling laws for interpreting results of small-scale movable bed models of beach change have yet to be determined (Hughes 1984; Sayao, 1984; Vellinga, 1984). Thus, data sets from laboratory experiments performed with small-scale facilities are of limited value for establishing quantitative understanding of profile change in nature.

Large wave tank (LWT) facilities enable controlled reproduction of near-prototype conditions of beach slope, wave height and period, turbulence induced by wave breaking, and resultant sediment transport and beach change. The problem of scaling is eliminated, and the required high-resolution measurement of the profile can also be attained. Disadvantages associated with wave tanks include contamination by reflection from the beach and wave generator and formation of wave harmonics (Buhr-Hansen and Svendsen, 1975). Experience suggests that these factors are negligibly small under reasonable experiment design.

Experiments using LWTs have been performed with monochromatic waves (Saville, 1957; Kajima *et al.*, 1983; Dette and Uliczka, 1987a; Kraus and Larson, 1988; Lee *et al.*, 2011) and with irregular waves with random heights and periods (Vellinga 1986; Dette and Uliczka, 1987b; Uliczka and Dette, 1987). Irregular waves will most closely reproduce naturally occurring profile change. Irregular waves introduce additional independent parameters associated with the wave spectrum, whereas in monochromatic wave tests the effects produced by the basic parameters of wave height and period can be isolated and systematically investigated. Hughes and Chiu (1981) discuss theoretical and practical problems associated with use of irregular waves in movable bed modelling.

Previous studies (Kajima *et al.*, 1983; Kraus and Larson, 1988) have also made available two independent data sets on beach profile change from experiments performed using LWTs and monochromatic waves. These experiments involved combinations of waves, water levels, beach slopes, and sands of the scale that exist in the field, but with the advantages of true two-dimensionality, control of the external (wave) force, and an optimized measurement schedule.

2.7.2. Field approach

Field data sets useful for quantitative study of beach profile change are extremely rare because of the required high resolution in time and space of morphology and associated wave climate and water level. Due to the great spatial and temporal variability of waves and the three-dimensional character of nearshore bathymetry in the field, it is difficult to extract conclusive cause and effect relationships between waves and profile change resulting solely from the wave-induced, cross-shore component of sediment transport. Recently, several studies (Yates *et al.*, 2009; Roberts and Wang, 2012; Schipper *et al.*, 2016; Utizi *et al.*, 2016; Marinho *et al.*, 2017a; Marinho *et al.*, 2018a) have reported results from repetitive concurrent field measurements of the beach profile, waves, and water level. However, alongshore spacing between cross-shore measurements is typically hundreds of meters, and the time interval between surveys is on the order of months, during which wave conditions and water level varied substantially. Marinho *et al.* (2018a) have quantified several morphological beach changes along regularly nourished Portuguese coastal stretch, but very few direct correlations with the waves and water level could be done due to a low spatial and temporal resolution of the measurements. Wright *et al.* (1985) made daily observations over 6-1/2 years of Narrabeen Beach, Australia, and related gross change in nearshore morphology to a single parameter, the dimensionless fall speed.

Several numerical models of beach profile change have been developed based on field observations and measurements. Such mathematical models have been widely used, first as a tool for designing interventions schemes (involving nourishments or any other engineering structure) and then for selecting optimal coastal management strategies. Ideally, to address such demands, high-quality data sets (*e.g.* morphological details of bathymetry and topography related to wave and wind climate from the same time period) are required, which consequently depends on systematic and comprehensive monitoring programs. By establishing characteristic scales and patterns of beach-change morphology (*e.g.* beach-fill response), greater insights may be gained into the mechanisms of interaction between the seabed and forcing regimes as well as the governing processes determining the beach evolution.

2.8. Coastal adaptation strategies

To reduce the coastal risk, two main complementary actions have been consistently recommended by several national documents addressing technically and scientifically the Portuguese littoral and its management (ENGIZC, GTL, GTS, POC's): mitigate the erosion process by means of artificial beach nourishments and act over the occupation in a way to reduce the risks faced by the seafronts through accommodation and relocation strategies. These official documents, requested by the government, expose vulnerabilities and risks of the coastal zones as well as ways to preserve the coastal resources in order to promote its sustainable development.

In respect to coastal protection, two main options have been considered as the most realistic (GTL, 2014): 1) maintenance of a reactive policy based on hard engineering structures and/or located interventions, similar to what has been made in the past; 2) adopt a strategy based on artificial nourishment as principal measure for sediment cycle replenishment. Also, whatever new strategy is adopted, it is highly recommended that the previous solution is progressively dropped until the new alternative reveals efficiency. As previously discussed, the ongoing protection strategy is dominantly reactive, with the artificial nourishments becoming increasingly more frequent.

The reposition of the sediment budget has been analyzed in GTL (2014) as well as the possibility of relocation of the economic activities and urban areas exposed to risk, in a perspective of re-planning of the coastal zones at medium-long term. The same report develops cost-benefit and multi-criteria analysis in order to determine the alternative that best fits the maintenance of the shoreline position for short (2020), medium (2050) and long (2100) timescales. To evaluate the costs related to a strategy based on the continuity of the current protection policy, the annual average investment was estimated in the last 20 years. According to GTL (2014), to implement this strategy, 450 M€ would be needed during the period 2020-2050 in order to deal with the consequences from an increasing deficit of sediments and the subsequent eventual reinforcement of the existing coastal structures. On the other hand, to implement a strategy based on artificial beach nourishments, it is estimated an investment around 432 M€ (or 734 M€ if following a mega-nourishment approach). These costs obviously depend on the accessibility to the borrow sites and the magnitude of the operations. Comparing both strategies, the solution built upon nourishments becomes more attractive at long-term, since presents lower costs and minimizes the territory loss and the associated risk at the same time that brings benefits to the coastal zones, by providing opportunities for nature and recreation. Considering this scenario, GTL (2014) has estimated a cumulated sediment volume around 135 Mm^3 until 2050 (or 231 Mm^3 if following a concentrated fill approach), with Caminha - Nazaré, Cabo Raso - Cabo Espichel and Olhos de Água - Guadiana being the main coastal stretches to benefit from fill operations.

As a step further, after the main recommendations established by GTL (2014) and in a context of restructuring of the Portuguese administrative system and establishment of the new government, the legislative order 3839/2015, 17th April of the Environmental State Secretary has led to the development of a national study, designed as GTS, with the mission to outline the necessary diligences to the preparation of the first action focusing on high-magnitude nourishments in the most exposed Portuguese coastal zones. Generally speaking, GTS (2015) identifies priority zones for artificial nourishments, sources and presents a detailed characterization of the sediments that can be mobilized for nourishment effects by taking into account: sediment deposits in stock of harbors (resulting from past dredging operations), predicted maintenance/deepening of navigation channels (2015-2020), bypass operations from updrift to downdrift areas near Aveiro and Figueira da Foz harbors (2015-2020) and existing sediment sources in the continental platform (offshore sources). The same study also develops an analysis about the involved costs and possible financial supports, exploring a basis for creation of collaboration mechanisms between harbor entities and the APA. The priority areas taken by GTS (2015) are: Espinho-Torreira (the longest stretch with 22.4 km), Barra-Mira (totalizing 21.5 km), Figueira da Foz-Leirosa (9.7 km) and Costa da Caparica (4.2 km long between Cova do Vapor and Nova Beach/Saúde Beach). Given the high level of vulnerability and risk in these coastal areas, the fill operations will act with an immediate purpose to enlarge the beach and increase the level of protection of the uplands structures through sand replenishment. GTS (2015) has recommended a total amount of 35 Mm^3 of sand to be placed in the dry or subaqueous portion of the beach above the -10 m (CD) elevation contour. Table 2.5 depicts the proposed fill volume per each intervention area.

Table 2.5. Fill volumes affected to each coastal stretch (GTS, 2015).

Coastal stretch under risk	Fill volume ($x10^6$ m^3)
Espinho - Torreira	10
Barra beach - Mira	10
Figueira da Foz - Leirosa	10
Costa da Caparica	5

In case that it is only feasible the intervention in one of the coastal stretches mentioned above, the GTS (2015) defines the sector between Espinho and Torreira as priority, as a function of the intensity of the ongoing erosive process and its location, at the northern boundary of the sediment circulation cell, providing potential for feeder response of the nourishments to downdrift coastal stretches.

The first study appearing to prove the feasibility of long-term coastal adaptation strategies, relying exclusively on beach nourishment and growth, for the Portuguese littoral has been recently presented by Stronkhorst *et al.* (2018). The study evaluates two main beach fill strategies under different climate change scenarios, accounting for erosion and SLR impacts of up to 0.5, 0.7 and 1.9 m by 2100: 1) the hold-the-line strategy, in which shoreline retreat is directly re-established by means of local nourishment operations; and 2) the sand balance strategy, encompassing fill operations performed on a regular basis (each five years) at high-value locations, with volumes equal to the sand deficits due to sea level rise and other known structural sediment losses. The study was carried out for the Aveiro coast (cell 1b), between Esmoriz and Quiaios, constituting a coastal stretch approximately 90 km long. The main results of this study suggested that large-scale sand nourishments might be a feasible method in combination with a policy of managed retreat for low-value areas in order to avoid expensive locked-in situations. According to Stronkhorst *et al.* (2018), the sand balance strategy is considered the most practical and has the advantage of economy of scale and a smaller number of impacted locations along the coast. For example, the “Sand Motor” project, in The Netherlands, was engineered to last several decades and the unit price per m^3 of sand was lower (€3/m^3, 2011 price; Stronkhorst *et al.*, 2012) than in regular sand nourishment projects

(5-10€/m^3, Jonkman *et al.*, 2013). Simultaneously, fewer locations are being disturbed with sand disposals over time.

Despite the encouraging results presented by Stronkhorst *et al.* (2018) and the governmental recommendations to establish a long-term political strategy, there is still little experience with large scale fills along the Portuguese coast. It has to be kept in mind that in a long-term perspective, the accommodation and the managed retreat adaptation strategies might be also needed, as well as alternative funding sources (not only public). Coastal adaptation measures will require studies of combined protection solutions, accommodation and relocation strategies for the coastal zones, based on the modelling of the coastal processes, especially for higher-risk coastal stretches, and on cost-benefit and multi-criteria analyses (Santos *et al.*, 2017; Stronkhorst *et al.*, 2018). For these reasons, it is urgent to develop integrated assessments of various adaptation methods and to estimate the costs associated with different adaptation scenarios for longer timescales (2100). In this respect, studies based on comparative analysis of solutions found to be successful in other countries, as well as the possibility of sharing funding responsibilities between central government institutions, local governments and private entities may contribute to develop alternative models for the financing of adaptation of the Portuguese coastal areas.

2.9. Summary

This section summarizes the current knowledge previously presented and highlights some gaps of particular relevance to this study. The past and recent evolution of the Portuguese littoral has served to stress the numerous problems that many beaches currently face. Over the years, an arbitrary and somewhat reckless coastal development, deriving from a disarticulation between developed research and planning/management needs, aggravated by the fact that the latter is not always in line with the rigorous (or slow) work of the scientific research, has resulted in beaches becoming narrow engineering projects sustained by constant maintenance and ongoing expenditures. By trying to hold the shoreline in position, a large number of hard-engineering structures were built in the past, mostly along the northwestern coast of Portugal, changing the natural beach landscapes and the natural movement of sand and waves. These practices have prevented a flexible response to wave forcing and sea level rise, which has resulted in a “change of mind” related to the way that the beaches are being managed.

More recently, technical and scientific experts behind government agencies, and consequently engineering consultancies, are turning to increasingly expensive sand replenishment programs which dump thousands of tons of dredged sand, mostly coming from maintenance/deepening activities of navigation channels of harbors, on existing nearby eroded beaches. However, a conscious intervention demands solid knowledge about the different coastal processes behind it. Unfortunately, when it comes to the design and performance evaluation of beach fills, there is still limited historical information available about past interventions and resulting coastal evolution. Most of the knowledge related to fill operations is empirical, meaning that related issues like the effectiveness of distinct nourishment schemes (focusing on different profile features, *e.g.*, the dune, berm, shoreface and bar), the short- and long-term fate of the fill material (determining initial adjustments and lifetime, respectively) and re-nourishments requirements (frequency and volumes) still need to be resolved. As the time goes on, the sea level rises, and the beaches become narrower, more beaches are expected to be under stress. In that light, monitoring becomes a concern. The role of monitoring for establishing quantitative understanding of the beach morphology change in nature has been clearly pointed out in Section 2.6. The information presented previously evidences that monitoring and access to data is a very complex theme and should be developed considering the three main components of the sustainable development of the coastal areas: social, economic and environmental. A management policy sustained by follow-up programs is of major importance and has been extremely encouraged to get a better judgment over the coastal zones. Although some steps have been taken towards the implementation of monitoring programs, in order to promote a learning-by-doing approach, in Portugal, this issue is still in an early stage of development.

The importance of the monitoring data is also related to its potential for the development and validation of numerical coastal evolution models. However, in the absence of such information, numerical models are usually taken as a valid representation of a certain reality. For this reason, qualitative and quantitative understanding of beach profile change is extremely pursued for improving numerical model performances and predicting potential land loss rates or shoreline retreats.

In line with the research interests of the present study and considering the general guidelines of the ongoing national protection strategy, where artificial beach nourishments are taken as preferential coastal protection method, the following chapter introduces in deep the concept of working with nature solutions.

CHAPTER 3

ARTIFICIAL SAND NOURISHMENTS

Chapter structure

3. ARTIFICIAL SAND NOURISHMENTS

Maximizing opportunities and reducing frustration are the fundamental principles of a recent way of thinking and acting known as *Working with Nature* (WwN). The concept was born under the auspices of PIANC in 2008, as an attempt to identify ways of achieving the project objectives in an ecosystem context by working with natural dynamic processes to ensure environmental protection, restoration or enhancement outcomes, rather than avoiding or minimizing the environmental impacts of a pre-established design. The specifics regarding WwN are set out in the PIANC (2008). The approach consist in a fully integrated process which seeks to identify and exploit win-win solutions, by respecting the nature and making meaningful use of stakeholder engagement. WwN is designed to be proactive from a very early stage of project development (conception), as soon as main objectives are known (before the initial design is established), through to project completion, in order to maximize opportunities that best benefit navigation and nature and – importantly – minimize frustrations, delays and associated extra costs. WwN philosophy defends therefore, that the project goals are put firstly in a perspective of the natural systems, rather than in a perspective of technical design, constituting a paradigm shift from “fighting” the forces of nature with engineered structures to “working with nature” and providing “room for sustainability” instead (Kabat *et al.*, 2009).

Soft measures of coastal protection usually appear under the shadow of the WwN concept. Restoring eroding beaches through the use of artificial nourishment techniques have been highly recognized as an environmentally friendly solution for combating coastal erosion and maintaining valuable ecosystems which are under risk of being lost, as beaches, wetlands, reeds, and nesting areas (Figure 3.1). This type of technique has a long history in the United-States, where it progressively became the preferred method for shore protection (Campbell and Benedet, 2006; Pranzini and Williams, 2013). Also, in many countries in Europe, sand nourishments projects (also referred to as artificial nourishment, beach fill, or beach replenishment) has been one of the most extensively used shoreline protection solutions, especially in Spain (Silveira *et al.*, 2013), Belgium (Mertens *et al.,* 2008), Germany (Hanson *et al.*, 2002) and notably in The Netherlands, where nourishment experiences date since mid-1970’s (Hanson *et al.*, 2002). Artificial nourishment projects are engineered to work like natural beaches, allowing the fill material (usually sand) to shift continuously according to the dynamics dictated by changing waves and water levels (CHEDRC, 2017). This sand, once placed, is gradually redistributed by natural processes towards a new equilibrium state, pushing the shoreline seaward and consequently contributing to alleviate erosion (CHEDRC, 2017).

a) Nourishing the subaerial portion of the beach.

b) Nourishing the subaqueous portion of the beach

Figure 3.1. Artificial sand nourishments projects (Pinto *et al*., 2018).

The chapter started with a brief introduction to the *working with nature* concept, in which artificial sand nourishments fall in. In line with this integrated approach, the information gathered in following subsections go through relevant issues associated to artificial sand nourishments (ASN) projects by providing a succinct explanation about what the ASN interventions are, what they do and how they work considering their main design purpose, as well as a general descriptive overview of the environmental, societal, economic and recreational related-costs and benefits. Special attention is given to important design aspects like different fill placement schemes and borrow sediment sources types, as they can determine the longevity of the operations and/or increase significantly the cost of the operations. Afterwards, some examples of ASN applications are briefly accounted in Portugal, regarding disposal techniques, sediment source and responsible entities. The chapter ends with the presentation of some international case studies of particular interest that have become a worldwide reference.

3.1. Objectives

In pair with the hard coastal structures and non-structural solutions such as relocation or retreat (management strategies that restrict the building and coastal development), artificial beach nourishments projects work to protect the upland (inhabitants, property and existing infrastructures) against the advance of the sea. This solution is typically faced as a sustainable coastal protection measure because it is the only one from all the available methods that adds new sediments to the coastal system, when coastal erosion is mainly attributed to a negative balance in the littoral system. These sediments are brought to the littoral system from outside sources (*e.g.* offshore, navigation channels, terrestrial, bypassing) to feed the littoral drift and restore an eroding beach by advancing or holding the shoreline position. Importantly, the artificial sand nourishments projects do not remove the physical forces that cause erosion, but simply slow erosion down by mitigating its effects.

According to the definition adopted by Pinto *et al.* (2018), artificial sand nourishments are designed for two main purposes: 1) mitigate erosion and related risks of the coastal zones; and/or 2) enhancement of the water resources and environment. When aiming at the mitigation of the coastal erosion, these interventions are specifically engineered to: 1) contain or advance the shoreline position; 2) reduce vulnerability to overtopping/flooding; and/or 3) protect hard engineering structures. In the first case, the addition of sediments is essentially seen as a method to replace the sediment budget and attenuate the shoreline retreat. The placement of the sand can be carried out in the subaqueous portion of the beach, as an offshore mound for dissipating the wave energy near the shoreline, or in dry portion of the beach, as an attempt to create an area more exposed to wave climate, preventing high up attacks on the beach profile (dunes, cliffs and infrastructures). In rocky littorals, this latter deposition solution also allows for widening the beach seaward which consequently encourages the beach use further away of the cliff bottom, minimizing the exposure level of bathers to the risk of mass movements (landslides, etc.). In the second case, to reduce vulnerability, the placement methods usually focus on the beach-dune system for reinforcement of the obstacle/barrier effects of high-up portions of the beach. Robust berms and dunes protect the upland from overtopping, during extreme events (storm surges and hurricanes), helping to hinder episodes of dune breaching and consequent flooding and property damage. Finally, in the presence of heavy engineering structures, fill operations are usually taken as an additional and complementary measure to mitigate the negative effects caused by these structures. Also, the sand deposition is typically performed in the subaerial portion of the beach, as a way to create a new area that prevents the direct attack of the waves over the structures, contributing also to its conservation and longevity (Pinto *et al.*, 2018).

On the other hand, when nourishments projects are primarily oriented to the enhancement of the natural endogenous resources, the fill operations seek to: 1) increase the beach width and promote the recreational activities; and/or 2) protect the natural/cultural resources (Pinto *et al.*, 2018). In both cases, the sand is typically placed in the dry portion of the beach (berm). This will allow widening the beach for recreational uses and consequently increasing the carrying capacity of the beach for bathers as well as prevent that the waves reach the natural resources that must be preserved (natural habitats, marine species) or even cultural properties.

Following this classification, Figure 3.2 shows that, over the last 20 years (1998-2017), more than half of the nourishment interventions carried out in Portugal was undertaken for stabilization purposes of the shoreline position, whereas approximately 26% aimed at increasing the carrying capacity of the beach. The third most popular motivation for applying nourishment interventions is the need for reducing coastal vulnerability and risk to overtopping/flooding events, corresponding to 11% of the total interventions performed. Figure 3.2 was obtained through analysis of the specific objectives associated to each nourishment intervention, undertaken in the past two decades in Portugal, inventoried by Pinto *et al.* (2018). However, whenever an intervention was engineered for more than one specific purpose, the number of intervention (=1) was equally divided per each specific objective (for example, two specific objectives representing 0.5 interventions each). Artificial nourishments interventions show less applicability along the Portuguese coast when they are oriented for the protection of hard coastal engineering structures as well as the protection of natural/cultural resources, corresponding to 2% and less than 1%, respectively.

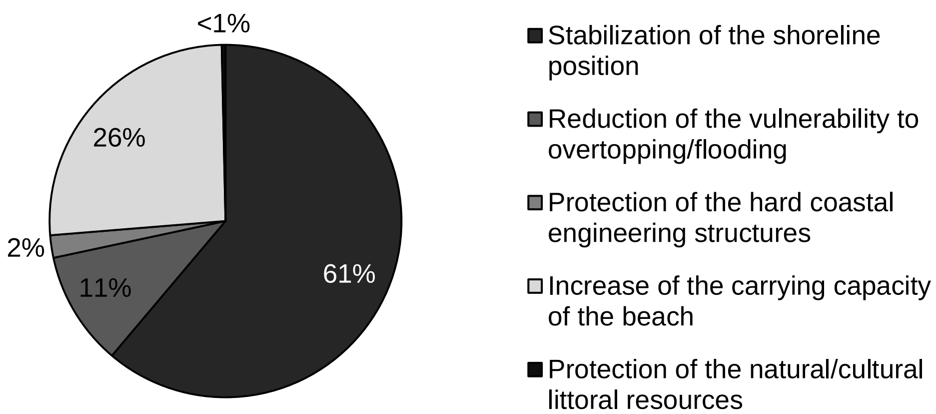


Figure 3.2. Distribution of the number of artificial nourishment interventions according to the specific design objective (time series 1998-2017), based on Pinto *et al.* (2018).

Artificial beach nourishments may be also applied in emergency situations due to urgent repair requirements (*e.g.* for beach recovery after severe storm-induced damages) or as a long-term management strategy at a regional scale, *i.e.*, to mitigate the generalized erosion tendency recorded as well as the coastal vulnerability to climate-related changes (*e.g.*, an acceleration in Sea Level Rise, SLR).

3.2. Behavior/performance

The factors that control the behavior and evolution of artificial sand nourishment projects may vary from case to case, spatially and temporally (Bird and Lewis, 2015). Nourished beach changes evolve fast, and sometimes can generate public discontent and dissatisfaction as well as some political and social criticism when the fill volume is placed at the beach and after a minor storm disappears (Pinto *et al.*, 2018). From a morphological point of view, this is not erosion, although some coastal stakeholders have a different opinion, regarding the nourishment project as a failure. It is a natural process for nourished beaches and dunes to erode and change as they dissipate and absorb wave energy during a storm (CHEDRC, 2017). For this reason, Verhagen (1992) recommended that disposal activities should be carried out following an approach, in which changes after a storm are expected to be small, as an attempt to get more support from society.

According to Weggel (1995), an artificial nourishment project typically last from 3 to 10 years, depending on the location, type of the project and intensity of the storms (Pinto *et al.*, 2018). The time elapsed between the deposition date and the loss of 50% of the total disposal volume is designated by half-life of the operation (Leonard *et al.*, 1990; Pinto *et al.*, 2018) and can be used as a durability measure of the feeding property of the project when evaluating its behavior and longevity (Elko *et al.*, 2005; Pinto *et al.*, 2018).

According to CUR (1987) and Pinto *et al.* (2018), the initial losses (taking place during the first year after construction) for nourished beaches can vary from 10% to 20%. Based on the behavior of nourishment projects in northwestern Europe, Verhagen (1996) suggest a range from 1 to 25% for initial sediment losses. In Portugal, a series of nourishment interventions carried out in Algarve from 1998 through to the present have recorded around 10-40% of initial sediment losses (Teixeira, 2011; 2016).

When nourishing the subaerial portion of the beach, the visible fill volume losses (*i.e.* the sediments that are subtracted to the dry portion) occurs due to (Gravens *et al.*, 2003): 1) short-term losses associated to the natural readjustment of the beach profile towards a new equilibrium state and compaction of the sand after deposition; 2) losses by longshore sediment transport gradients, driving sediments outwards of the disposal zone; and 3) natural seasonal morphological variations of the beach and occurrence of high-energy events (storms).

Recognizing the positive attributes of sand nourishments in promoting beach growth, as well as their wave dissipation function and restoration of nesting habitats for endangered or threatened sea species, reports on artificial nourishments performance along the world's coastline have been given by, for example, Zwamborn *et al.* (1970), McLellan (1990), Bodge *et al.*, (1993), Otay (1995), Foster *et al.* (1996), Dean (2002), Gravens *et al.* (2003), Barnard *et al.* (2007), Ojeda *et al.* (2008), Yates *et al.* (2009), Park *et al.* (2009), Silveira *et al.*, (2011), Brown *et al.* (2016), Bergillos *et al.* (2017), Hoonhout and De Vries (2017), Marinho *et al.* (2018a), Ludka *et al.* (2018), Botton *et al.* (2018), Bergillos *et al.*, (2018) and Spodar *et al.* (2018). As attested by several of these authors, it is difficult to predict the degree of success and performance level of the nourishment operations, in part due to the uncertainty and unpredictability of the occurrence of extreme wave climate events. Although the disposal material becomes part of the littoral system, benefits to the beach and adjacent areas have not been well quantified. Unfortunately, the study of beach nourishment projects is very complex, and several gaps related to the understanding of their behavior in response to changes in the forcing conditions, nourished sediment grain sizes, disposal location and maintenance frequency still remain, requiring the need for further research.

3.3. Costs, benefits and impacts

In order to properly quantify the costs and benefits associated to nourishment interventions, all the potential impacts arising from such operations in the coastal zones have to be set and analyzed in a societal, economic and environmental perspective and compared with other coastal protection strategies (via hard structures and/or non-structural methods). For example, besides combating coastal erosion and protecting people and property, as aforementioned, through storm damage reduction, sand nourishment interventions can also bring numerous environmental, recreational, and aesthetic benefits to the beach. Nourishing and widening an eroding beach can: protect threatened or endangered plants in the dune area; protect habitat behind dunes or next to beaches; create or restore habitat lost through erosion, for sea turtles, shorebirds, and other beach organisms; and create new nesting areas for endangered sea turtles and spawning grounds for other species (CHEDRC, 2017; Pinto *et al.*, 2018). Beach nourishments projects can also be successful in the long term, by providing opportunities for recreational activities such as fishing and boating, with considerable benefit in terms of appeal for tourists. Healthy and wide beaches are not only essential for the tourism industry but also can help boost local economies by increasing property values, residential rentals, retail sales, and demand for services (CHEDRC, 2017). It is also important to underline that one of the biggest advantages of the nourishment interventions in relation to the other solutions relates to its feeding of downdrift beaches. Although the nourishment have limited durability (being designed to protect an specific area during a certain time period), as long as the nourished beach is eroded and the fill material runs out from the deposition site, longshore gradients will continuously transport this material to adjacent beaches, serving to combat erosion at downdrift areas.

Nourishment interventions are engineered to optimize the potential coastal protection benefits. However, it has to be kept in mind that a nourishment project able to protect against any and all storms is not only impossible to design but also economically unfeasible (CHEDRC, 2017). There are numerous factors that can increase significantly the expenditures associated to the beach fill operations: type of borrow site, grain size of the nourished sand, limitations on sediment availability, the placement techniques, lifetime for which the nourishment is designed to be "active" (*i.e.* volumes needed to fulfill the design purpose), erosion rates, and the interval between re-nourishment projects. For instance, when a specific beach fill volume is required to ensure coastal protection and flooding control, using finer nourished sediments might turn the project more costly to maintain, because sorting by waves and currents will tend to move finer nourished material towards offshore and coarser sand onshore. This latter case will contribute to the increase of the beach width, providing more resistance to erosion (by means of more intense wave refraction and reflection processes), although it might affect the recreational use and the aesthetics of the beach. On the other hand, the further borrow site is located from the deposition site, the more expensive the transportation costs will be, being extremely recommended anticipated reflections regarding this issue when selecting the suitable material for a particular project (during the project conception stage) in order to optimize the travel costs.

The design objectives of the nourishment project, as well as the fill placement techniques required to meet such goals, have also a large influence on the project costs, which in turn are also decisive when selecting the suitable borrow material. For example, the use of offshore sources to nourish the dry beach portion, for the purpose of increasing the beach width, may turn the project more expensive, since distinct equipment may be required to ensure accessibility to the beach (or deposition site). Also, access to terrestrial deposits might require road constructions or improvements of existing routes, in order to ensure safety in the transportation of large sand volumes (Gravens *et al.*, 2003). Furthermore, the interval between re-nourishment volumes requirements is typically specified based on the average expected losses over the lifetime of the project, as well as on the maximum volume of sediments that the borrow source can provide (sediment availability). Naturally, the longer the desired project lifetime is, the larger the amount of required fill volume will be, having a proportional impact on the construction costs. However, a favorable physical environment (in terms of wave climate and morphological characteristics) might increase the re-nourishment interval, reducing costs. Conversely, high erosion rates and/or littoral drift capacity may turn nourishment operations financially impractical (Gravens *et al.*, 2003).

According to Pinto *et al.* (2018) a nourishment project involves a deep sediment mobilization, either at the borrow source area and/or at the disposal site. The mobile nature of the sea bottom subtract (sands) generally implies the presence of benthic marine communities that must be taken into account and may represent constraints to the project. In the phase of sediment extraction, the impacts are mostly reflected over the biological communities that are naturally dredged along with the sediments, consequently displaced from their natural habitat and deposited in the fill placement site, resulting in a high mortality rate, with partial or total destruction of the species. In the case of the southern coast of Algarve, a study with focus on the benthic communities elaborated five years after the exploration of the borrow source located offshore of Vale do Lobo beach, showed that the period elapsed was enough for total recovery of these communities (Gonçalves *et al.*, 2004; Pinto *et al.*, 2018). In the phase of deposition of the dredged sediments, the construction of a new beach may affect the indigenous communities in many different ways, either for direct impact through burial of the benthic communities (when placing the fill material), or indirectly over the remaining species (*e.g.* seabirds) which depend on these benthic communities to survive (Peterson and Bishop, 2005; Pinto *et al.*, 2018).

Nevertheless, species that live in the littoral correspond to resilient communities with high tolerance to the environmental constraints and strongly adapted to the high sediment dynamics (Pinto *et al.*, 2018). Additionally, the dredging and deposition operations cause temporary disturbs and it has been recognized that, after the loss of the original habitats, the organisms are capable to recover in a short time period, taking place sometimes a spatial displacement of these habitats or a recolonization of the affected sites (Teixeira *et al.*, 1998; Greene, 2002; Gonçalves *et al.*, 2004; Speybroeck *et al.*, 2006; Gaspar, 2014; Pinto *et al.*, 2018). Through the right choice of both dredging and disposal approaches (by varying the techniques and schedules of these operations), it may be possible to minimize the direct impacts over the marine communities, for example, through conduction of the dredging and disposal activities in phase, absence of mechanic compaction of the deposited sand, or through execution of these activities during a season with less biological productivity, allowing a quicker recovery of these organisms (Gonçalves *et al.*, 2004; Speybroeck *et al.*, 2006; Pinto *et al.*, 2018). During the planning process the design team of artificial nourishments must evaluate these complex environmental issues and find ways to maximize benefits and minimize the related-costs, and ensure that the project fulfils the goals for which it was designed.

3.4. Fill placement techniques and re-nourishment requirements

According to CHEDRC (2017), the beach fill design needs to be established by taking into account a bunch of factors: climatology, the shape of the beach, type of native sand, sediment transport volumes and rates, erosion patterns and causes, wave climate characteristics and water levels, historical data and previous storms, probability of certain beach behaviors at the site, existing structures and infrastructure, and past engineering activities in the area. By gathering all this information, coastal engineers will be able to understand coastal processes taking place above and under water and consequently, calculate the volume of beach fill needed, determining also how long the nourishment will last before re-nourishment operations are required. Re-nourishment efforts may differ from site to site, as a function of the morphological conditions of the beach as well as the frequency and intensity of storms from year to year (CHEDRC, 2017).

Typically, the beach fill design involves re-building one or several of the following beach profile features with sand: the dune, beach berm, active profile, and nearshore bar (Figure

3.3). The first technique usually involves the reinforcement of an existing natural dune by adding elevation and/or cross-sectional area, or building an artificial barrier where none existed beforehand (Figure 3.3a). As the natural dune recovery process occurs at a much slower rate than storm-induced changes, these interventions are commonly required after extreme storm events to replace dune sediments that have been transported seaward by the power of high-energy waves. Also, artificial dunes are designed to naturally function as a protective barrier of the upland property, helping to prevent overtopping and flooding events.

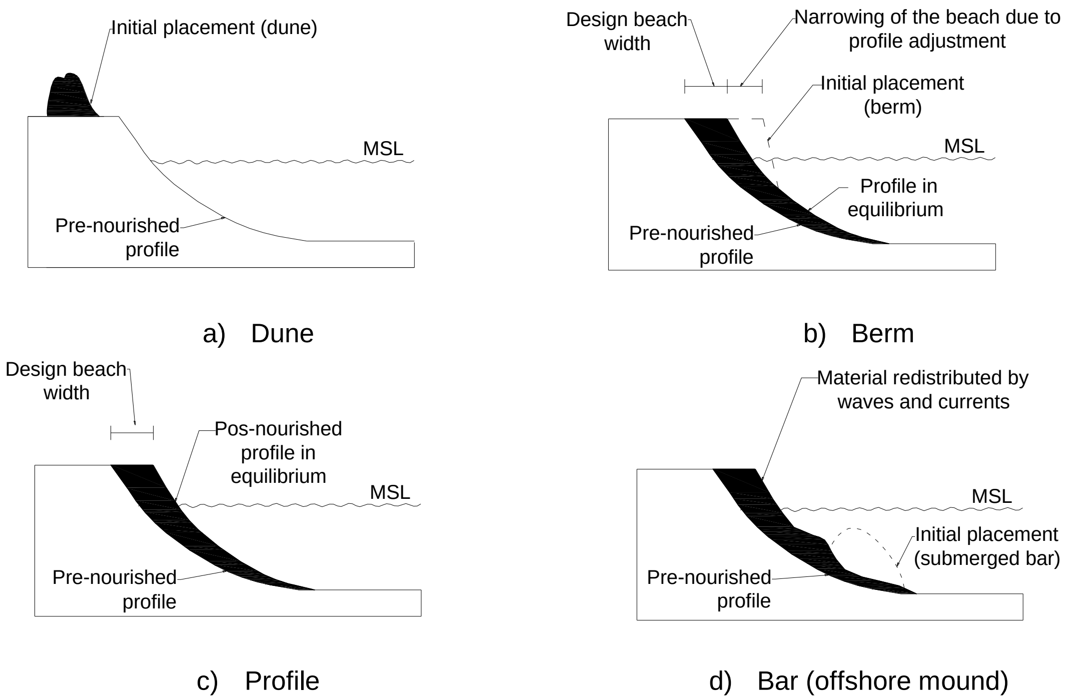


Figure 3.3. Designs of artificial sand nourishment schemes (adapted from Gravens *et al.*, 2003 and Marinho *et al.*, 2018b).

Nourishing the beach berm consists on the primary feature included in most beach fill projects, which usually focus on the widening of the beach (*i.e.* a seaward translation of the shoreline), with a higher or lower elevation of the crest, for dissipating storm wave energy (Figure 3.3b). The nourished sand is concentrated on the visible portion of the beach. This method is sometimes referred to as the overbuilding method, since a decrease of the beach width is expected during the initial fill adjustments.

The third construction method is the profile nourishment (Figure 3.3c), where in principal, sediments are placed along the entire active profile covering wet and dry portions of the cross-section. In this type of method, the use of distinct moving-equipment (terrestrial and maritime) to assess different discharge points usually increase the total cost of the fill operations.

The final technique, nearshore placement (Figure 3.3d), is usually undertaken in connection with dredging operations (*e.g.*, maintenance activities in navigation channels) because large volumes of material can be made available at low costs through the economic use of standard dredge equipment for distribution of the fill (*e.g.*, hopper dredger or split-haul barges). The sand is placed nearshore of the beach by creating an artificial bar along a finite length, often with a shore-parallel alignment, which will act as a barrier for dissipating incident wave energy. With a proper design (shallower than the depth of closure), the nourished sand will be set in motion by waves and migrate onshore (under certain wave conditions) until eventually it becomes part of the beach berm and beach face system (Gravens *et al.*, 2003).

Although, a range of different fill construction methods can be used, techniques for fill placement should be optimized to best serve the specific requirements and primary objectives of the project. The disposal typology may be also influenced by logistic, operational and financial constraints. In Portugal, half of the beach fill operations carried in the last two decades have been focusing on the subaerial portion of the beach, representing in total 48 operations and 50% of the total fill volume mobilized for nourishment purposes (see Figure 3.4). This result is justified by the predominance of artificial nourishment interventions designed essentially for stabilization purposes of the shoreline position and increase of the beach width (see Figure 3.2).

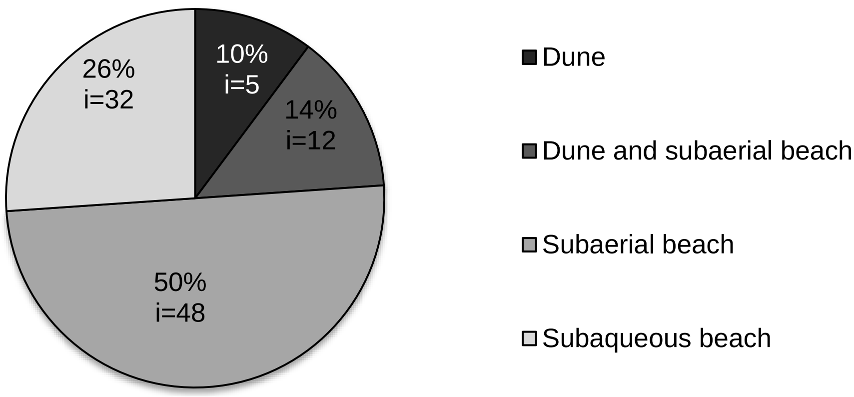


Figure 3.4. Distribution of the nourishment volumes and intervention number, i, according to the disposal technique (time series 1998-2017, based on Pinto *et al.*, 2018).

3.5. Borrow sources and transportation for deposition

Any artificial nourishment operation needs to define the location from which the fill material will be obtained. Such locations are commonly designed as borrow sources. According to Gravens *et al.* (2003) and Veloso-Gomes (2011) these sources can be divided into 5 main categories: terrestrial, backbarrier, offshore (zones with water depths greater than 20-30 m), navigation channels (“sediments of opportunity” of harbors) and bypassing/backpassing.

Often, the implementation of nourishment interventions is conditioned by logistic and operational reasons intrinsically associated to the nature of the borrow sources (Pinto *et al.*, 2018). According to Pinto *et al.* (2018), the borrow sources are located near the fill placement area and present compatible sediment properties with the native beach sand (*e.g.* grain-size distribution).

The characteristics of the sediments used for nourishment are of particular importance for the success of the project, once they can directly affect the beach profile shape and influence the fill evolution (Creed *et al.*, 2000; Gravens *et al.*, 2003). Also, the sediments have to be of good quality, *i.e.*, they cannot present risk of organic contamination and heavy metals (Pinto *et al.*, 2018). If possible, the sediments compatibility must be safeguarded through the use of sediments with a grain size in order of magnitude or slighter greater than the native sediments (CUR, 1987; Dean, 2002; Gravens *et al.*, 2003; Teixeira, 2011; Pinto *et al.*, 2018). In this way, the behavior of the fill operation will present a compatible behavior and in equilibrium with the hydro- and morphodynamic conditions at the deposition site (Pinto *et al.*, 2018).

Considering the information provided by Pinto *et al.* (2018), in Portugal, artificial nourishments are usually performed though the use of “sediments of opportunity”, obtained from projects whose primary goal was not beach nourishment. This material usually corresponds to sediments that had been already predicted to be dredged in the context of harbor activities, and their use is mandatory for nourishment purposes in nearby downdrift beaches. The borrow sources typically results from dredging operations undertaken for maintenance/deepening of navigation channels and tide bars, exploration of land sand deposits in the area of harbor administrations (resulting from previous dredging activities), and offshore sources through extraction of sand from deeper sea bottoms. In some cases, the use of sporadic bypass systems (considering trucks or dredgers) has been also applied to transport sediments from locations with an intense accumulation of sand (*e.g.* updrift zones of harbors) to downdrift areas, where beaches have become depleted of material through erosion. Following this classification, Figure 3.5 displays the distribution of the sand volumes in Portugal, in the last two decades, according to the type of borrow source.

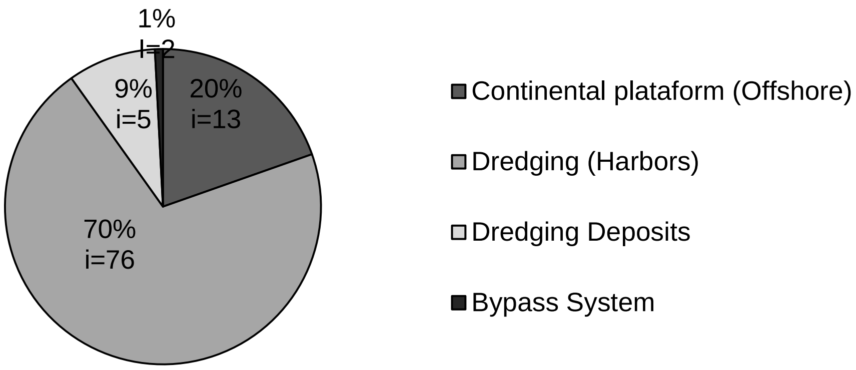


Figure 3.5. Distribution of the nourishment volumes in Portugal and intervention number, i, according to the type of borrow source (time series 1998-2017, based on Pinto *et al.*, 2018).

As can be verified through Figure 3.5, the biggest slice of the fill material comes from regular harbor/fishing/recreation dredging activities, representing approximately 70% of the total sand volume that has been mobilized during the last two decades for nourishment purposes (≅14 Mm^3 of sand). Continental platform (offshore) is the second most representative borrow source, corresponding to 20% of the fill material volume, followed by inland deposits (dredging deposits) and bypass systems, with 9% and 1%, respectively. Contrary to the borrow sources deriving from harbor/fishing/recreation activities, Pinto *et al.* (2018) refers that obtaining sediments from the continental platform presents several constraints from the operational, logistic, environmental and financial points of view. As concluded by Pinto *et al.* (2018), the use of this type of borrow source implies previous studies for detection of accessibility and availability of suitable and compatible material with the native sand of the beach, which justifies a lower frequency of this type of borrow source. Sediment bypassing is the less applied borrow source for nourishment projects, counting with only two national projects with this nature: Pedra Alta beach (Viana do Castelo) and Belharucas beach (Albufeira). The sediment bypass was carried out from the sand accumulated in the updrift side of the northern breakwater of Pedra Alta, in the first case, and in the updrift side of the Vilamoura marine, in the second case. In both cases the sand was deposited downdrift, in the subaerial portion of the beach, through punctual interventions using a truck and dredger, respectively.

As mentioned in Section 3.3, the transportation of the borrow material is one of the most important aspects to be considered when designing nourishment projects. The transportation of the fill material to the desired deposition site constitutes a technical procedure, with large influence in the total cost of the project.

When nourishment projects are carried out in connection with dredging activities, several techniques can be adopted for direct sand disposal: dumping/discharge through opening of the dredge basement, pumping by pipeline (using floating, submerged pipes or a combination of both), or through the use of repulsion systems (rainbow or jet disposal). There are also mixed solutions involving a first discharge in subaqueous beach portion and consequent pumping to the beach and dunes (re-handling procedure). In this case, the dredging material typically obtained by means of a trailing suction hopper is stored in the nearshore (intermediate station - booster), then, a cutter suction dredge pumps the material to the beach or dune (Veloso-Gomes, 2011). However, this procedure requires favorable wave climate and suitable water depths in order to be able to conduct the operations. It is the responsibility of the coastal engineers to study which equipment are required and which constructive methods are considered the most suitable for dredging, transport, pumping and re-profiling of the beach features (Veloso-Gomes, 2011). The deposition techniques should reduce as much as possible the water turbidity.

On the other hand, EUrosion (2006) refers that transportation of the fill material carried out via land route typically implies high-costs and significant negative impacts due to the usual traffic that is generated (round trip) when moving large volumes of sand. In this case, the transportation costs, the potential damages in the roads, and the traffic conflicts are directly proportional to the distance covered by the vehicles (trucks).

3.6. Examples of past nourishment interventions in Portugal

In this section, some Portuguese artificial nourishment interventions carried out in the past for different purposes are briefly described according to their main focus, direct costs, responsible entity and derived outcomes/results. For more detailed information, the references given in the text should be consulted.

The first example to be enumerated is the beach fill intervention carried out in D. Ana beach, in Algarve region, in 2015 (Figure 3.6). According to Pinto *et al.* (2018), this project was designed for two main purposes, the stabilization of the shoreline position, and the increase of the beach width for bath/recreational use. The operations involved the deposition of approximately 0.14 Mm^3 of sand deriving from an offshore source located near the dumping site. The cost of the project was around 1.8 M€ and all the operations were conducted by the Portuguese Environment Agency (APA).

Figure 3.6. Nourishment intervention in D. Ana beach, Algarve (Pinto *et al.*, 2018).

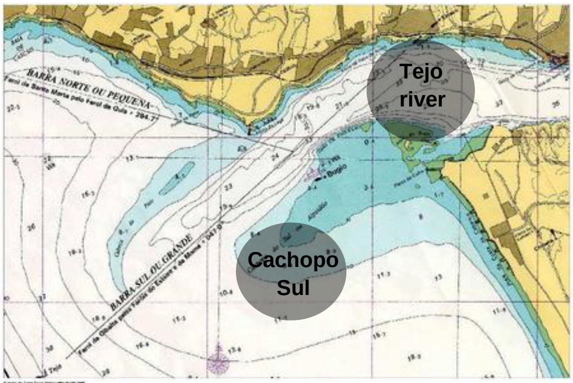
Two years after the conclusion of the operations, besides the reduction of the frequency of the impact of the wave in the bottom of the cliffs, a significant reduction of risk to the bathers was verified: the bathers start to occupy a beach area closer to the sea, leaving the adjacent areas to the cliffs. An increase of the carrying capacity of the beach was also achieved (Pinto *et al.*, 2018).

The second example corresponds to the project requalification of the lagoon system of Ria Formosa, carried out in 1999/2000, with the prime purpose of reducing vulnerability to overtopping and flooding mechanisms, Figure 3.7 (Pinto *et al.*, 2018).

Figure 3.7. Ria Formosa, Algarve (Pinto *et al.*, 2018).

This project consisted of the distribution of approximately 1.88 Mm^3 of sand along the beach and dunes of a set of barrier islands of Ria Formosa (peninsulas of Ancão and Cacela, islands of Cabanas, Tavira and Armona), operations that were later complemented with the construction of palisades and walkways (Pinto *et al.*, 2018). The fill material was taken from the main channels of Ria Formosa. After implementation, the project served to reduce the occurrence of overtopping events and the erosion rates, as well as promote dune growth. The Institute of Conservation of Nature and Forests (ICNF) was the main responsible for the operations (Pinto *et al.*, 2018).

Another important and very well-known case of Portuguese beaches artificially nourished is Costa da Caparica beach, located near Lisbon, on the Portuguese west coast (Figure 3.8). Between 2007 and 2014, fill operations, involving the deposition of approximately 3.5 Mm^3 of sand, were phased out (2007, 2008, 2009 and 2014) for control of the shoreline retreat and protection of the hard engineering structures located nearby (Pinto *et al.*, 2012; Pinto *et al.*, 2015; Pinto *et al.*, 2018). The material to perform the fills, dredged from the southern channel of the Tejo river and from Cachopo Sul (in the entrance of the Tejo Estuary, see Figure 3.8a) were placed in the subaerial beach of São João da Caparica and in the urban beaches of Costa da Caparica, between the 1st and 7th groin (Figure 3.8b). This project, which cost almost 20M€, has mainly contributed to mitigate the erosion effects and combat the shoreline retreat at São João da Caparica beach, as well as to increase the stability of the coastal stretch. The operations undertaken enabled also the creation of a new beach area, which in turn has provided extra protection to the existing longitudinal revetment structure (Pinto *et al.*, 2018).



a) Borrow sources.

b) Nourishment operations.

Figure 3.8. Nourishment operations in Costa da Caparica beach, in 2008.

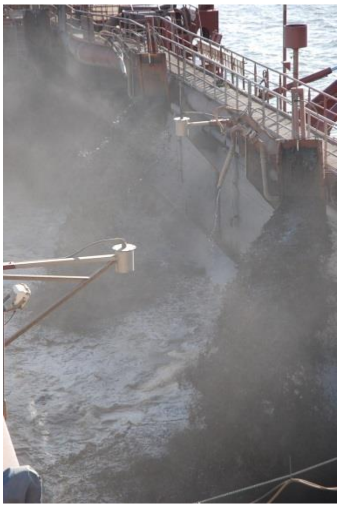
The fourth example to be pointed is the nourishment project carried out in Tróia Peninsula, in the winter of 2006/2007. Tróia Peninsula is a southeast-northwest oriented coastal sand spit, approximately 25 km long and between 0.5 and 1.5 km wide, located on the northern sector of the Tróia-Sines sedimentary cell 5c) (see Figure 2.3). This intervention was engineered to increase the dry-beach width as an attempt to enhance the level of protection to erosion and increase the area of beach available for recreational purposes. The project encompassed the deposition of approximately 200 000 m^3 of sand made available by dredging operations undertaken for the construction of a new marine basin in Tróia and local excavations. Given the beach-quality of the dredged sediments, considered by the time a “sediment of opportunity” source with sand compatible with the native beach material and suitable for beach fill, and given the proximity to the dredging site, the ocean-side beaches were the preferential site for the deposition of the dredged sediments (Silveira *et al.*, 2013). These beaches are the most visited beaches in this peninsula and face the large ebb-tide delta of the Sado river that develops adjacent to the inlet (Figure 3.9).

Figure 3.9. Beach nourishment in Tróia.

The sand was placed along approximately 600 m of shoreline by either pumping or truck haul, mostly on the upper part of the beach profile in order to create a wide berm to act as a buffer to protect the cultural heritage of Roman Ruins archaeological site (Silveira *et al.*, 2011). According to Silveira *et al.* (2013), who reported of the first two years following the conclusion of the intervention and assess its efficiency, the intervention has prevented the aggravation of the erosive process and helped to increase the dry-beach width, protecting the archaeological heritage of Tróia. This, in turn, has promoted dune field growth and development with the same beach quality as before (Silveira *et al.*, 2013). As Troia Peninsula is undergoing a great tourism development, serving as the stage for a casino, hotel and tourist apartments, a golf course and several other service areas, as well as it represent a huge financial resource, the main responsible for this project was Sonae Turism, SGPS, S.A.

Barra-Vagueira, a 10 km coastal stretch, located in the northwest coast of Portugal is the last example to be highlighted, since nourishment projects are regularly undertaken in connection with maintenance activities of the Aveiro harbor (Figure 3.10). Between 2009 and 2015, approximately 3 Mm^3 of sand have been dredged from the Aveiro navigation channel and dumped in different locations to alleviate the erosion problems observed at downdrift beaches of the inlet. The majority of the nourishment operations have been carried out through the combined use of dredging and disposal activities. In order to reduce the logistics involved in these operations, dredged material are typically disposed in the subaqueous portion of the beach through opening of the dredge basement. As an attempt to assess their impacts related to the coastal system, a monitoring program involving data collection has been established to track the evolution of the nearshore nourishments. All of these operations, undertaken in a regular basis, together with all the monitoring data collected, will be the “object of study” in the Chapter 4.

a) Dredging of the Aveiro navigation channel.



b) Filling of the dredger basement.

Figure 3.10. Dredging operations of the Aveiro inlet.

During the last 20 years, the Harbor Administrations and the Ministry of the Environment have been the main promotors of the beach fill operations, being responsible for 90% of the projects designed (see Figure 3.11). Municipalities and Private entities assume less representativeness, corresponding each to only 5% of the total number of interventions (see Figure 3.11).

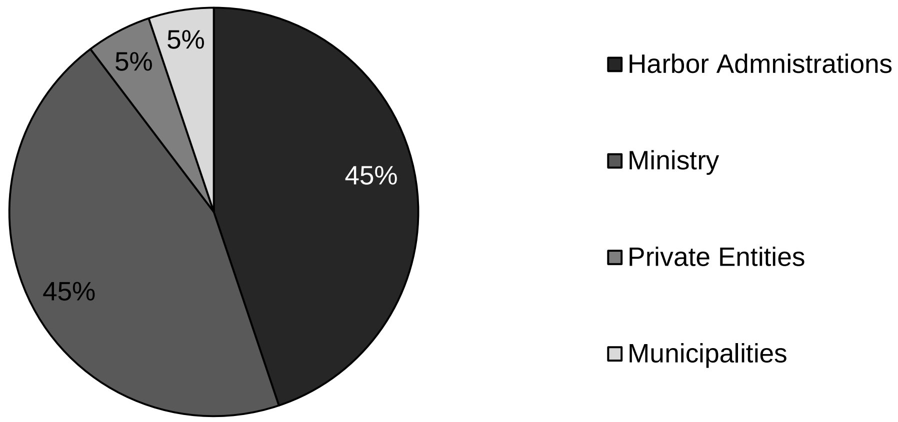


Figure 3.11. Entities responsible for carrying out the nourishment projects in Portugal, between 1998 and 2017 (Pinto *et al.*, 2018).

3.7. International cases studies

The current risk situation that is observed in numerous Portuguese beaches, especially in the northwest coast, where the sediment deficit gains more attention, may require solutions that can have, under some circumstances, exceptional characteristics. It is fundamental to anticipate alternative design solutions that appeal to the innovative capacity of the Portuguese society. This section presents two international artificial nourishment case studies known for their innovative and sustainable approaches for maintaining coastal protection. These projects illustrate good practices and have been showing high potential for accommodation and protection to their corresponding coastal areas, which in turn may serve in further understanding regarding coastal adaptation strategies to be implemented in Portugal.

3.7.1. Sand Engine, Netherlands

The worldwide growing-interest for the use of artificial beach nourishment to combat erosion, enhance coastal safety and increase beach width has been demanding new coastal maintenance approaches which in turn, have encouraged several ongoing pilot projects. An international example of these is the pilot project based on a mega-nourishment approach, known as "Sand Engine" (completed in 2011), which was originally designed to assess the effectiveness of concentrated fills (in time and space) on protecting the Dutch coast (Stive *et al.*, 2013; Schipper *et al.*, 2016). Being the first of its kind, the project consisted in the deposition of 21.5 Mm^3 of dredged sand in the form of a large sandy peninsula and two shoreface nourishments. Dredging vessels picked up the sand 10 km offshore and pumped it into the project area (Taal *et al.*, 2016). The main part (19 Mm^3), the mega nourishment, was shaped as a large hook-shaped peninsula with the outer tip curved towards the north (Figure 3.12), whereas 2 Mm^3 and 0.5 Mm^3 were used for the northern and southern additional shoreface nourishments, respectively. This shape of the mega-nourishment project was inspired by the potential of the coast to provide areas for nature and recreation. The hook-shaped peninsula was designed to provide resting areas for seals at the end of the spit, with a shallow lagoon to offer habitats for flatfish. Part of the sand would be transported onshore, promoting the development of pioneer dunes, with associated vegetation, along the beach (Ecoshape, 2018).

The initial area after construction was 100 ha, but the goal for this project was set in 35 ha of new beach/dunes after 20 years. The total dumping volume (21 Mm^3) was calculated based on the expected erosion rate for the Dutch coast over the 20-years design lifetime specified for this project. The idea of this new nourishment technique was to dispose a significant amount of sand in a certain location, which would then be gradually redistributed across and along the shore by the power of winds and currents. Through the use of natural processes to redistribute the sand, this intervention aims to limit the disturbance in the local ecosystems at the same time that it provides coastal protection and new areas for nature and recreation (Ecoshape, 2018). According to Ecoshape (2018) the traditional approach to nourishment obeys to re-nourishments procedures every five years, resulting in frequent disturbance of the ecosystem. However, following a strategy of concentrating fill operations the nature is disturbed much less frequently than in the standard five-year cycle and there is more time for the development of new ecosystems with more biodiversity (Ecoshape, 2018).

In 2011, the project was completed (Figure 3.12a) and since then, it has been monitored on a regular basis, and subjected to extensive research in order to document and assess its natural evolution, as an attempt to translate this experience into generic knowledge to be applicable elsewhere (Ecoshape, 2018, ZANDMOTOR, 2018). According to Schipper *et al.* (2016) and Ecoshape (2018), monitoring results show that so far, the Sand Engine is behaving as predicted: sediment is indeed being transported along the coast (Figure 3.12b), seals have been visiting the area and a rare plant species has been found growing on a newly formed juvenile dune. Observations show that the sandy hook soon began to bend and extend towards the shore, leaving a narrow feeder channel for the lagoon parallel to the beach (Figure 3.12b). After 18 months the project was completed, along the outer perimeter of the peninsula the shoreline retreated 150 m, with some locations showing a retreat up to 300 m. Simultaneously, the shoreline advanced by up to 200 m in the adjacent coastal sections, resulting in an increase of the alongshore extent of 1200 m (50% increase). The surveys show that the volumetric losses on the nourished peninsula were 1.8 Mm^3, *i.e.* about 10% of the added volume. The majority (70%) of the volumetric losses in sediment on the peninsula were found to be compensated by accretion on adjacent coastal sections and dunes, confirming the feeding property of the nourishment. According to Schipper *et al.* (2016), the morphological response was strongest in the first 6 months while the planform curvature and the surf zone slope reduced. In the following 12 months changes were less pronounced. Overall, the feeding property was related to incident wave power, such that months with high-energy waves result in more alongshore spreading. Months with small wave heights resulted mostly in cross-shore movement of the nourished sediment.

a) 1 month after completion (Aug-11) b) 15 months after construction (Oct-12)

Figure 3.12. Sand Engine pilot project (mega-nourishment approach).

3.7.2. Nerang Sands Bypass System, Australia

In the particular case of Portugal, one of the aspects requiring technical advance, in order to be able to establish an effective sediment management policy along the Portuguese northwest coast, relies on how to solve the problem of sand transferring (herein also referred to as sand bypassing or simply as bypassing) from accreted areas at the updrift side of Aveiro lagoon and Mondego mouth to the downdrift beaches (GTL, 2014).

In fact, the majority of sand bypassing is done in association with littoral barriers, *i.e.*, natural inlets, stabilized inlets and harbors, with all of them interrupting the longshore transport of sediments. One of the main problems caused by inlets and harbors stabilized with jetties is the erosion at downdrift beaches. In this light, sand bypassing systems become a very important concept. Artificial sand bypassing is a man-induced technique of transferring of sand across inlets, from the jetties fillets, shoals, or navigation channels to the downdrift beaches, by mechanical or hydraulic means (Clausner, 1999; Melton and Clausner, 2004). Sand bypassing is typically performed by using dredges (floating plants), although dedicated land based facilities designated as fixed sand bypassing plants provide an alternative that has been successfully used around the world (Melton and Clausner, 2004). Although sand bypassing using fixed plants is relatively rare from a worldwide perspective, there is a fair number of sites where they might be viable. However, the effort required to estimate costs and performance is significantly greater with fixed plants than simply modifying a navigation dredging contract for downdrift beach placement.

There are numerous worldwide examples (Boca Raton, FL, USA; Oceanside harbor, CL, USA; Durban, South Africa; Amanohashidate coast, Japan; Hvide Sande, Denmark; Marina di Carrara, Italy; Nagapattinam, India; Playa de Castilla beach, Spain, etc.), but what is thought to be world's largest sand bypassing system operates at the mouth of the Nerang river in Queensland, immediately south of the Gold Coast Waterway entrance, Australia (Boswood and Murrray, 2001). This bypassing system began its operation in 1986 and was the world's first fixed sand bypassing system capable of operating in all weather conditions, still remaining at the leading edge of sand bypassing technology (Cowper and Thomas, 2014). This fixed bypassing project was constructed in conjunction with the training of the entrance and so, there was no erosion as a result of the entrance. Before training of the inlet, there was a progressive movement of the entrance northwards at a rate of 20 - 40 m per year. The bypassing system consists of a 500 m long jetty with 10 vertical jet pumps spaced along its length (Figure 3.13) and buried in the sand (fixed). The sand bypassing system encompasses a remote sea water supply pump station, a jet pump recovery system, a flume transfer pipe, a transfer pump station and a sand transfer pipeline. The system runs automatically overnight, and sometimes weekends, to take advantage of cheaper electricity rates and the discharge point is on an undeveloped part of an island, therefore having no direct effect on beach users. The jet pumps run on rails attached to the steel support piles to allow for installation and removal for maintenance work. The system was designed to pump a maximum of 500 000 m^3 of (*in-situ*) sand per year, with a peak monthly volume of 200 000 m^3 of sand. These values were specified taking into consideration the prevailing wave direction in the area, inducing a littoral drift of sand northwards along the coast averaging about 500 000 m^3 per year. Without any intervention, the sand would build up against the southern groin until eventually flowing around the tip of the groin and forming sand bars in the entrance to the newly created Gold Coast Seaway. The conventional solution would be to periodically dredge the entrance but this method could not be guaranteed to keep the entrance navigable at all times (Cowper and Thomas, 2014).

Figure 3.13. The Nerang Sand Bypassing System.

The jet pumps pump sand/water slurry vertically up into a sloping flume, which transfers it by gravity to the land based transfer pump station, to feed a conventional centrifugal slurry pump. This pump then pumps the slurry through a pipeline laid under the entrance to the north for discharge on to the beach (Cowper and Thomas, 2014). During its lifetime of operation the system has been extremely successful. It has proved capable of continuous operation during the most severe storms and has transported to date more than of 17 Mm^3 of *in-situ* sand.

The Nerang Sand Bypassing system requires a jetty structure. More recently Slurry Systems embarked on the development of a significantly cheaper sand bypass concept, not requiring a jetty. Under specific studies, this concept can be applied more universally to the majority of ocean entrances.

3.8. Summary

This chapter went through many cross-cutting issues related to artificial nourishment projects, providing a retrospective regarding the most important design aspects of artificial sand nourishments schemes that may impact socially, economically and environmentally on coastal zones. The objectives, the deposition typology and the type of the borrow source involved in beach fill design project were briefly discussed following a historical perspective at the national scale, accounting with the sand nourishment interventions performed in the last 20 years (1998-2017). This has served to summarize how the nourishment projects has evolved and contributed, increasingly, for the optimization of the integrated management of the coastal zones.

In short, Portuguese nourishment interventions have been essentially engineered for advancing or holding the shoreline position and/or increasing the beach width, *i.e.*, as an erosion mitigation measure and/or as a mean for enhancement of the littoral and creation of new recreational areas, corresponding to approximately 87% of the fill operations carried out in the last two decades. In line with that, it was demonstrated that half of the beach fill operations have been focusing on the subaerial beach (berm), summing up to 50% of the total fill volume mobilized for nourishment purposes. It was also shown that the Government (Ministry of Environment) and Harbor Administrations assume the monopoly in terms of concretization of this type of intervention, the latter representing the most significant slice in terms of sediment borrow sources (deriving from dredging harbor activities). This fact have stressed the use of “sediments of opportunity” for fill operations, obtained from regular harbor operations and whose primary goal is not beach nourishment. Continental platform (offshore) has appeared as the second most representative borrow source, corresponding to 20% of the fill material volume, followed by inland deposits (also resulted from harbor activities) and bypass systems, with 9% and 1%, respectively. All the statistics discussed in this chapter, obtained using the data documented by Pinto *et al.*, (2018), have evidenced that the majority of the interventions correspond to unique and isolated interventions in time, sometimes in a context eminently reactive for mitigation of the negative effects caused by storms, although some coastal areas nourished in a regular basis were also identified. These areas correspond mostly to downdrift areas of harbors because of their privileged location (near the navigation channels), reducing the transportation costs, as well as the erosion problems that are typically found nearby (deriving from the interruption of the natural sediment transport alongshore).

Importantly, although an effort to combine the use of the dredged material with the nourishment needs of eroding beaches has been made, taking advantage of the "sediment of opportunity" to minimize the operational costs, the economics and benefits referred to artificial beach nourishment projects are still under-researched, leaving still a gap between the useful information provided by scientists and the one demanded by decision makers. In order for knowledge to become relevant for planners and managers, the studied processes as well as the potential impact of artificial nourishment have to be set in a societal and environmental perspective, so that the various impacts are no longer regarded as isolated problems but as one of many societal implications of protecting the beach.

Deep down, the second and the third chapter of this dissertation stress a national paradigm shift regarding the national coastal management policy and the use of soft coastal protection measures in detriment of hard engineering structures. Based on efficient sediment management at the local and regional scale, it is believed that along certain coastal stretches in Portugal the equilibrium of the littoral system could be re-established through the encouragement and application of adaptive and innovative nourishment solutions (*e.g.* through implementation of a mega-nourishment or bypassing approach), as an attempt to contradict the long-term erosive tendency registered many decades ago. These chapters have also highlighted the importance of developing research with focus on coastal monitoring and coastal numerical modelling as a way to anticipate the behavior of beach fill interventions and consequently, select optimal nourishment strategies.

In the light of all that has been said, the study carried out further and presented in the following chapter is mainly dedicated to a case study, a sediment-starved Portuguese coastal stretch (Barra-Vagueira) which has been nourished on a regular basis in connection with maintenance activities undertaken by the Aveiro Harbor Administration.

CHAPTER 4

MONITORING CASE STUDY

Chapter structure

4. MONITORING CASE STUDY

Dredging operations are regularly undertaken for maintenance of existing harbors. In Portugal, since 2006, harbor administrations are obligated by law (49/2006, 29th August), when sediments are suitable and present good quality, to proceed to the reintroduction into the littoral system of the dredged material resulted from their regular operations through direct placement at downdrift areas, where beaches have become depleted of material. This measure was established as an attempt to mitigate the erosion problems typically caused by the presence of the harbor structures, as well as to maximize the benefit taken from maintaining depths or deepening activities of navigation channels. In this respect, monitoring becomes a concern since the combined use of dredging and disposal of dredged material may induce major changes in the beach morphology and generate unanticipated impacts in the environment, especially in a long-term perspective (Monge-Ganuzas *et al.*, 2013; Mateus *et al.*, 2016; Rehitha *et al.*, 2017). Although the potential use of dredged material for sediment replacement of eroding beaches is widely recognized, there is little comprehensive guidance available for engineers or planners regarding an adequate monitoring plan.

Monitoring is particularly valuable since it serves to objectively document and assess the performance of a project, determining how well it fulfills the requirements for which it was designed, and evaluate related impacts on adjacent shoreline (Capobianco *et al.*, 2002; Gravens *et al.*, 2003; Vacchi *et al.*, 2012). Analyses of monitoring data can also shed light on an adequate frequency of surveying, or even on the natural conditions that prompt the need for improving the project performance or developing potential design alternatives (Capobianco *et al.*, 2002; Castelle *et al.*, 2009; Vacchi *et al.*, 2012). Particular data of interest include topo-bathymetric surveys, waves and water levels, and characteristics of native and placed sediments. Beach profile surveys are essential for estimation and documentation of fill volumes and changes in the beach cross-section, allowing the prescribed sectional fill volume to be verified in compliance with the design specifications. Wave and water level data also provide valuable information for understanding project behavior and formulating solutions by establishing cause-and-effect relationships between the forcing conditions and the measured beach response. Beach sediment sampling is needed to determine sediment properties, for example, the grain-size distribution. This is of particular importance when the nourished and the native sand have different properties, which can directly affect the beach profile shape and influence the fill evolution (Creed *et al.*, 2000; Gravens *et al.*, 2003).

The dynamic behavior of nourished beaches as well as dredged areas, together with the need to ensure project functionality over the design life, requires a systematic monitoring plan to be established. However, in many cases they are not well planned or carried out in a comprehensive manner. A weak point of many monitoring schemes is that the surveys only cover a limited area (such as the dumping areas) and are not properly extended in the cross- and longshore directions. Consequently, a confident assessment of the impact of the project and the design efficiency may be compromised (Hamm *et al.*, 2002). Overall in Europe, the best monitoring practices are still those adopted in Dutch and German projects, which support regular monitoring activities (Hanson *et al*., 2002; Schipper *et al*., 2016; Blossier *et al.*, 2017). Apart from that, although the monitoring may be obligatory, beach nourishments in Europe are usually monitored during their early development, commonly one complete seasonal cycle, corresponding to the time that beach profile needs to reach a new equilibrium state (Larson *et al.*, 1999), and then once or twice a year (Hanson *et al.*, 2002; Yates *et al.*, 2009; Utizi *et al.*, 2016). Dean (2002) suggested a time interval between surveys of 1/2 year to 2 years, unless unusual behavior is expected. In USA, monitoring programs established to track the evolution of nourishment projects are typically undertaken over a few years, but on an annual to biannual basis, with few reports of monthly or seasonal variability (Bodge *et al.*, 1993; Browder and Dean, 2000; Yates *et al.*, 2009). Compared to Europe and USA, the estimated number of nourishment projects including monitoring programs in Australia is much smaller (Cooke *et al.*, 2012).

As seen in Chapter 2, in Portugal, the actual policy for safety assessment and erosion control is established by the Ministry of the Sea, which follows the Portuguese Environment Agency (APA) recommendations. The general practice is that there is no funding from private organizations for coastal protection. Thus, all costs are typically borne by the national government. The APA is responsible for issuing permits (designated through the Environment Impact Statements (DIA) - valid for two years) for coastal protection and other structures in the coastal zones, requiring anticipated studies of possible environmental-related impacts to the project proposal. Although a monitoring scheme is built into this legal structure and described in the DIA, due to the limited public financial resources generally devoted to coastal defense protection, regular monitoring of the coastline is usually neglected (Pranzini and William, 2013). Despite that the coastal management strategies still focus on a remedial rather than preventive policy, an overall long-term strategy for coastal management along the coast has been developed (see Section 2.8), anticipating follow-up programs (see Section 2.6.4).

In the present chapter, monitoring studies are carried out with a primary objective to examine the suitability of a dataset established by DIA in connection to a monitoring program developed for a Portuguese coastal stretch, regularly nourished with dredged material from maintenance activities of the Aveiro Harbor navigation channel, in northwestern Portugal (Figure 4.1). Attention is given to the beach morphology variability and sediment transport processes by examining temporal and spatial patterns of the nourished beaches and how they change (with focus on cross-shore profile and dumping area evolution). Time series of field measurements collected in connection to underwater nourishment operations performed along Barra-Vagueira coastal stretch are used and analyzed to investigate fill responses in medium- to long-term periods. This dataset encompasses topo-hydrographic surveys collected for 12 cross-sections (1 km spacing) located along the study area (between Sep-09 and Feb-15), as well as hydrographic surveys collected within the dumping areas (between Sep-09 and Apr-15). Geographic Information System (GIS) techniques and Empirical orthogonal functions (EOFs) are employed as the main tools to relate morphological changes, evolution trends, sediment budgets, sediment transport gradients, and short- and medium-term responses of the fills to the incoming wave conditions. The main findings exhibited throughout this chapter have been disseminated among the coastal community though publication of **Paper II** (Marinho *et al.*, 2017a) and **Paper III** (Marinho *et al.*, 2018a) - see appendices.

4.1. Field site: Barra-Vagueira coastal stretch, Aveiro, PT

Barra-Vagueira is a 10 km long coastal stretch, located on the northwest coast of Portugal, just south of the Aveiro harbor (see Figure 4.1). This stretch, approximately centered on the sandy coast between Espinho and Cabo-Mondego, is currently facing serious erosion problems. The proximity to the Aveiro lagoon and urban areas, the low-lying sandy topography, and the fragile dune system, susceptible to overtopping and flooding during energetic wave conditions and large tidal amplitudes, make this coastal stretch a vulnerable and exposed area to erosion (Coelho *et al.*, 2011; Pereira *et al.*, 2013). As a result, there is an imminent risk of breaching of the dune system that separates the Aveiro lagoon from the sea.

The serious erosion recorded is mainly related to a sediment supply deficit, which is resulting from the progressive weakening of the alluvial sources, and the sediment blockage induced by the presence of manmade structures (Coelho 2005, Coelho *et al.,* 2009a, Pereira *et al.*, 2013). The sediment input that under normal conditions would come from Douro river (near Porto) and feed the littoral drift towards south (estimated to be 1.5-2.0 million m^3/year, see Section 2.2), has been decreased to about 0.2 million m^3/year mainly due to the construction of hydro-power dams (Veloso-Gomes, 1991; Bettencourt, 1997; Andrade and Freitas, 2002; Coelho *et al.,* 2009a; 2009b; Costa and Coelho, 2013).

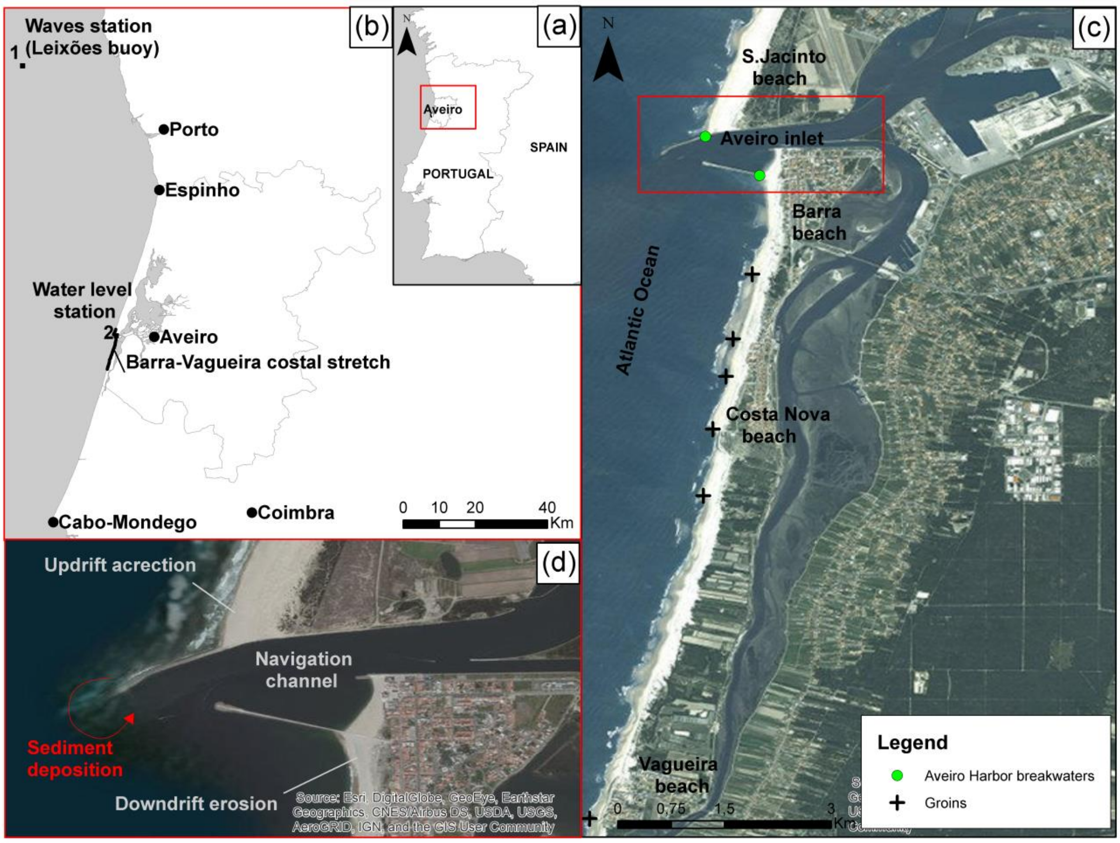


Figure 4.1. Location of the study site: (a) Portugal; (b) Aveiro district; (c) Barra-Vagueira coastal stretch; (d) Aveiro harbor navigation channel (zoom in the Aveiro inlet).

In terms of sediment dynamics, since the longshore sediment transport is interrupted by the Aveiro harbor breakwaters, strong accumulation of sand is occurring on the updrift (north) side, while a significant retreat of the shoreline occurs at the southern beaches (Barra, Costa Nova and Vagueira). This retreat is controlled by a groin field and a seawall along Costa Nova beach, and a seawall and a groin along Vagueira beach (Figure 4.1c). According to the long-term shoreline evolution study developed by EUrosion (2006), for a period of 10 years (1980-1990), the shoreline retreat rate in Costa Nova beach and Vagueira beach is estimated to be 3.7 and 3.9 m/year, respectively. The erosion rates vary over time: for the period 1996-2001, EUrosion (2006) indicates an erosion rate at north of Costa Nova and at Vagueira of around 6.6 m/year, while the Vagueira waterfront experienced a rate about 7.1 m/year; going back further in time, EUrosion (2006) refers an erosion rate at Aveiro of about 8.2 m/year when analyzing the shoreline movement between 1947 and 1958.

The beach profiles possess dominant seasonal variations and present intermediate to dissipative general morphodynamic behavior at north of Aveiro harbor and intermediate morphodynamic behavior at south (SNIRL, 2017). Mean sediment grain sizes along Barra-Vagueira coastal stretch range from medium to coarse sand in the subaerial part of the profile and medium to fine sand in the subaqueous portion. A study performed by Narra *et al.* (2015), involving 165 sediment samples collected at 5 different locations, along 3 cross-shore profiles over 8 months, in Barra beach, indicated that the dune base and the upper foreshore limit at high tide can have a d_{50} ranging from 0.2 to 0.4 mm and 0.3 mm to 1.7 mm, respectively. Narra *et al.* (2015) also concluded that the variability in the median grain size of the sediments found in higher levels of the profile is smaller than in deeper (underwater) areas.

4.1.1. Dredging/dumping operations and related harbor activities

In order to control beach erosion along the Barra-Vagueira coastal stretch and to improve the navigation channel conditions at Barra inlet, two major projects were undertaken by the Aveiro Harbor Administration – AHA (beyond the regular activities of navigation channel maintenance) between 2009 and 2015: "Dredging of Barra with reinforcement of the dune system" (AHA, 2009) and “Reconfiguration of Barra north breakwater” (AHA, 2013). During this time period (2009-2015) regular surveys of cross-shore beach profiles and the bathymetry of the dumping areas were undertaken and made available by AHA, which allowed for the monitoring of impacts related to the interventions.

The main objective of the first project was to dredge 1 million m^3 of sand (performed during two time periods, see Table 4.1) from the bottom of the inlet entrance of the Aveiro harbor and to use the obtained sand to reinforce the littoral system in the Costa Nova beach. The second major project conducted by AHA aimed at extending the north breakwater by 200 m, considering a new realignment of the navigation channel, carrying out dredging works to ensure safe navigation at a bed level of -12.5 m (Chart Datum, CD). The relationship between CD and Mean Sea Level (MSL) at Aveiro is given as MSL= CD + 2 m.

Table 4.1 summarizes the information related to the dredging and dumping operations carried out at Barra and Costa Nova beaches during 2009-2015. Some of the information described, related to the dates and volumes, was put together based on the interpretation of the design drawings and survey files made available by AHA in connection with the major projects undertaken.

Table 4.1. Details of the dredging/dumping operations performed during 2009-2015 (AHA, 2012; 2013).

Date of dredging/dumping		Source of the borrow material	Location	Volumes (m^3)
Year	Month			
2009	April/May	Navigation channel	DA2	500 000
	September/October	Navigation channel	DA2	500 000
2012	June	Breakwater construction	DA1	169 200
2013	May	Breakwater construction	DA2	66 700
	May	Navigation channel	DA1	79 100
	July	Navigation channel	DA1	251 700
	July	Navigation channel	DA2	1 008 100
	October	Navigation channel	DA2	97 700
	November	Navigation channel	DA2	101 600
2014	September	Navigation channel	DA2	64 800
	October	Navigation channel	DA2	110 600
	November	Navigation channel	DA2	148 300
	December	Navigation channel	DA2	208 200
2015	May	Navigation channel	DA2	137 800
	November	Navigation channel	DA2	188 300
	December	Navigation channel	DA2	106 400

The dredged material resulting from the channel and breakwater extension was deposited in the subaqueous part of the beach profile at two main sites. The first site, dumping area 1 (DA1), was limited by the south breakwater and the 1^{st} groin of Costa Nova beach (2012-2013), between bed levels -4 and -7 m (CD). The second site (DA2) was bounded by the 3rd and the 5th groins of Costa Nova (counting from north to south, Figure 4.2), between bed levels -2 and -5 m (CD).

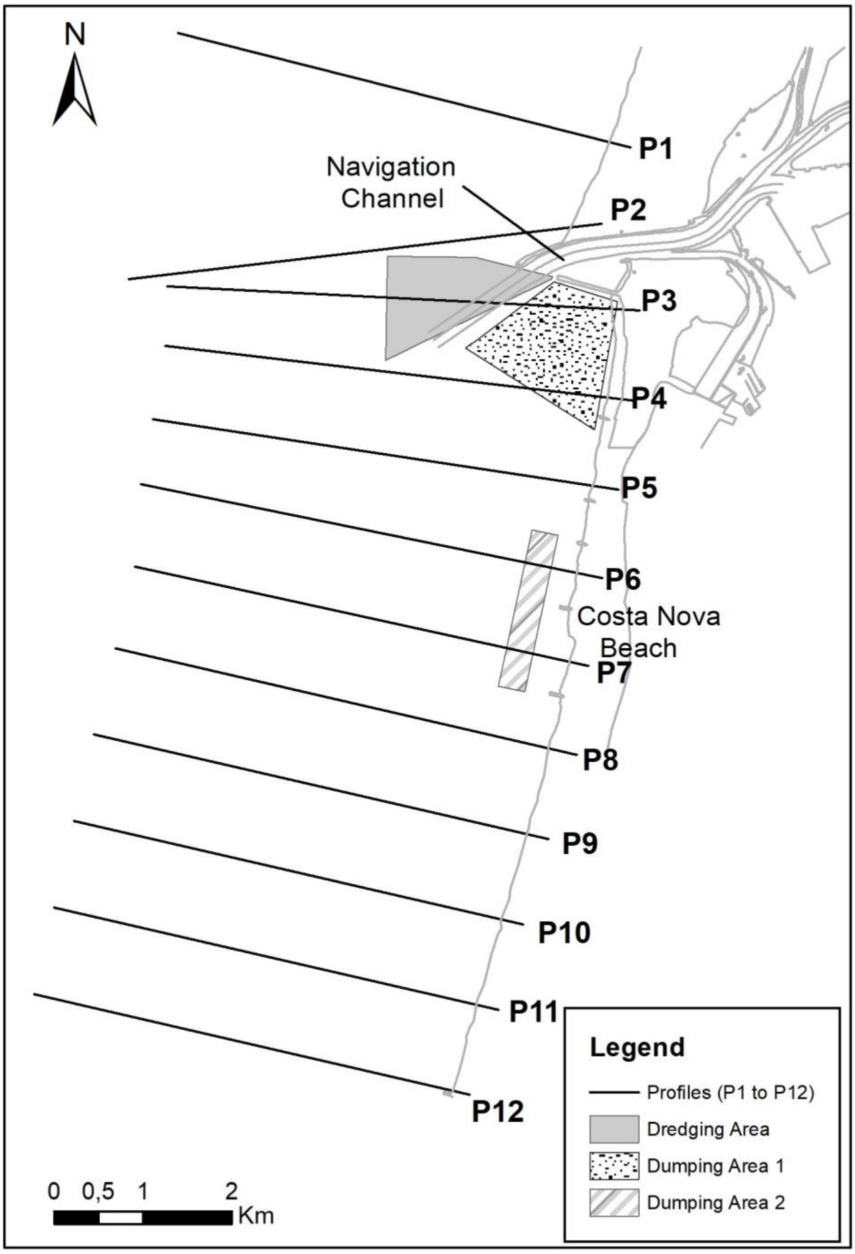


Figure 4.2. Location plan of the dredging and deposition areas and surveyed cross-sections (P1 to P12).

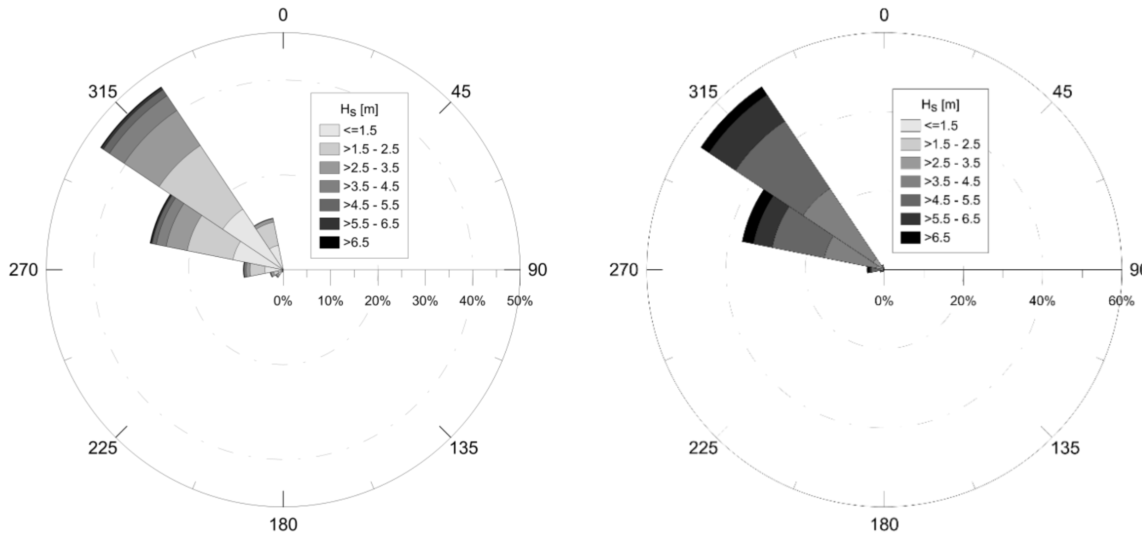
Since the borrow material was obtained mostly from the navigation channel and dumped in the subaqueous portion of the profile, the median grain size of the nourished sand placed in the Barra and Costa Nova beaches is considered similar to the native sediments (medium to fine sand). Besides the dredging and deposition operations detailed in Table 4.1, in 2014 the Barra-Vagueira coastal stretch was also nourished in the subaerial portion of the beach. The borrow material was moved from dredged sand deposits close to Aveiro harbor (located 4 km from the deposition spot) with trucks. Dredging operations detailed for 2015 were not included in the present study.

4.1.2. Wave climate

In general, the Portuguese west coast, which includes the coastal region of Aveiro, is heavily exposed to waves generated in the North Atlantic. Waves coming from the NW quadrant are the most frequent, occurring during about 80% of the year. The mean significant wave height is around 2-3 m, while the mean period is between 8 and 12 s. The tide regime is semi-diurnal, with an amplitude range between 2 m, during neap tides, and almost 4 m, during spring tides (Coelho, 2005; Coelho *et al.*, 2009b; Pereira and Coelho, 2013). During storms, especially common in winter, offshore significant wave heights, coming predominantly from northwest, may reach 8 m and persist for up to 5 days (Pires, 1989; Coelho, 2005; Coelho *et al.*, 2009b). Moreover, storm surges resulting from the influence of low-pressure systems can be frequent, but reaching 1 meter at the most (Coelho, 2005).

The wave regime at the Portuguese NW coast is obtained from data recorded at Leixões buoy, operated by the Portuguese Hydrographic Institute (IH). This buoy is located 78 km NNW far from Aveiro, at a depth of 83 meters (Figure 4.1). Wave data records from the Leixões wave buoy are considered to be representative for the offshore wave conditions at the study site (Narra *et al.*, 2015). Thus, time series of peak period (T_p) and associated wave direction (θ), significant wave height (H_s), and average period corresponding to H_s (T_{Hs}), at 3-hour intervals (normal data acquisition) and 30-minute intervals (storm data acquisition) were analyzed for the period corresponding to the field monitoring campaigns (Sep-09/Apr-15). In the analysis, it was assumed that records with significant wave height greater than 4.5 meters correspond to storm conditions. Figure 4.3 displays the distribution of the wave directions and wave heights for normal and storm conditions, respectively, for the period between Sep-09 and Apr-15.

Overall, time series of 3-hour records showed a maximum and average significant wave height of 8.89 m and 2.06 m, respectively, whereas the maximum wave peak period was around 18 s, with an average value of 11.05 s. Waves come mostly from the NW sector (46% of the observations) followed by the WNW (29%) and NNW (11%) directions. Regarding storm conditions, a maximum and average value for H_s of 9.21 and 5.42 m, respectively, were observed. The peak period reached an average value of 14.91 s and the NW and WNW sectors were the most representative, corresponding to approximately 90% of the observations (significant increase of the WNW quadrant to 38%).



a) Normal conditions (3-hours interval) b) Storm conditions (30-minutes interval)

Figure 4.3. Wave rose with energy based on significant wave height, H_s, measured at Leixões (2009-2015).

Seasonal variations indicate that waves coming from the SW quadrant are infrequent in summer and occur mainly during winter and transition periods (summer-winter and winter-summer). Figure 4.4 summarizes the average and maximum value of H_s, as well as the predominant wave direction sector for each month between Sep-09 and Apr-15.

Major storms (identified by the number of storm records for each month) hit the study area in Jan-13, Dec-13, Jan/Feb-14, Nov-14 and Jan-15. Most energetic winter conditions occurred between Dec-13 and Mar-14, registering maximum and average values for H_s of about 9.21 and 5.69 m, respectively. During these energetic storms severe damage and beach erosion were reported by the media for the study site.

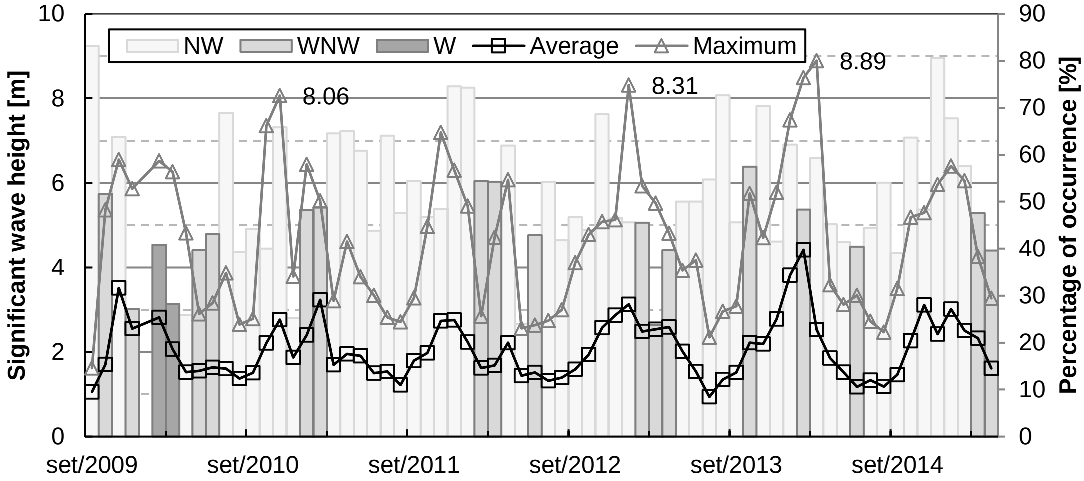


Figure 4.4. Monthly significant wave height and respective wave direction dominant sector. Bars represent the percentage of wave occurrence.

4.1.3. Monitoring program

Since 2009, a monitoring program has been conducted by the Aveiro Harbor Administration in connection with the dredging and dumping operations carried out at Barra and Costa Nova beaches. The monitoring campaigns encompassed beach profile measurements and bathymetric surveys covering the dumping areas. Profile surveying using a multi-beam echo-sounder (transducer of 200 khz and accuracy of 0.01 m ± 0.1% water depth) and a Real-Time Kinematic (RTK) global positioning system (GPS Leica GC15 RTK – with coordinate system transformation to local Datum 73) started in Sep-09, just before the second fill placement (Sep/Oct-09, Table 4.1), and continued until Feb-15, with approximately 1 year frequency between surveys. In total, 12 cross-sections (P1-P12) were surveyed with a spatial resolution of 1 km between survey lines from the updrift side of Aveiro harbor (S. Jacinto beach) to Vagueira beach (see Figure 4.2); two lines were located north of the Barra inlet (P1-P2; accreting beach) and 10 lines were located south of the harbor covering the Barra-Vagueira coastal stretch (P3-P12; eroding beach). From these 10 profiles, two of them are located between the southern breakwater and the 1st groin of Costa Nova (P3 and P4), one profile between the 1st and the 2nd groin (P5), the 3rd and the 4th groin (P6) and the 4th and the 5th groin (P7). The remaining eroding profiles are located southward of the 5th groin of Costa Nova. Each profile was surveyed from an alongshore base line located close to the top of the dune (backshore region) to a bed level -11 m (CD) or deeper. In addition, using a multibeam echo-sounder (transducer of 250 kHz, decimeter accuracy) bathymetric surveys were collected annually for the dumping areas, and just before and after the fill material was placed, spanning a total period of almost 6 years (Sep-09/Apr-15). Figure 4.5 details the dates and locations of the surveys.

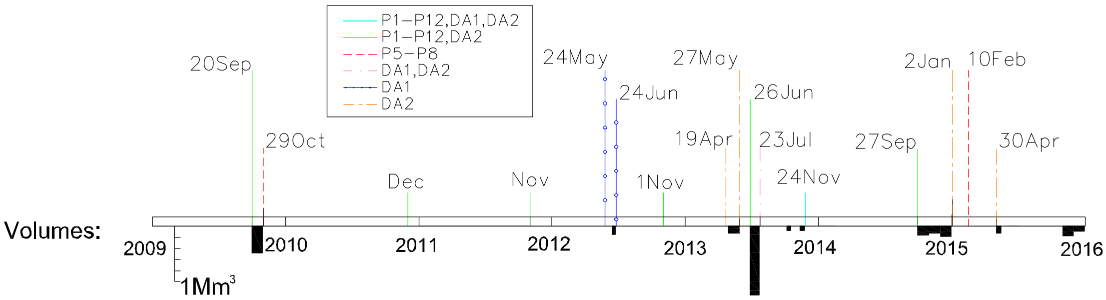


Figure 4.5. Timeline of the surveys performed at the study site (monitoring campaigns) and filling volumes at dumping areas.

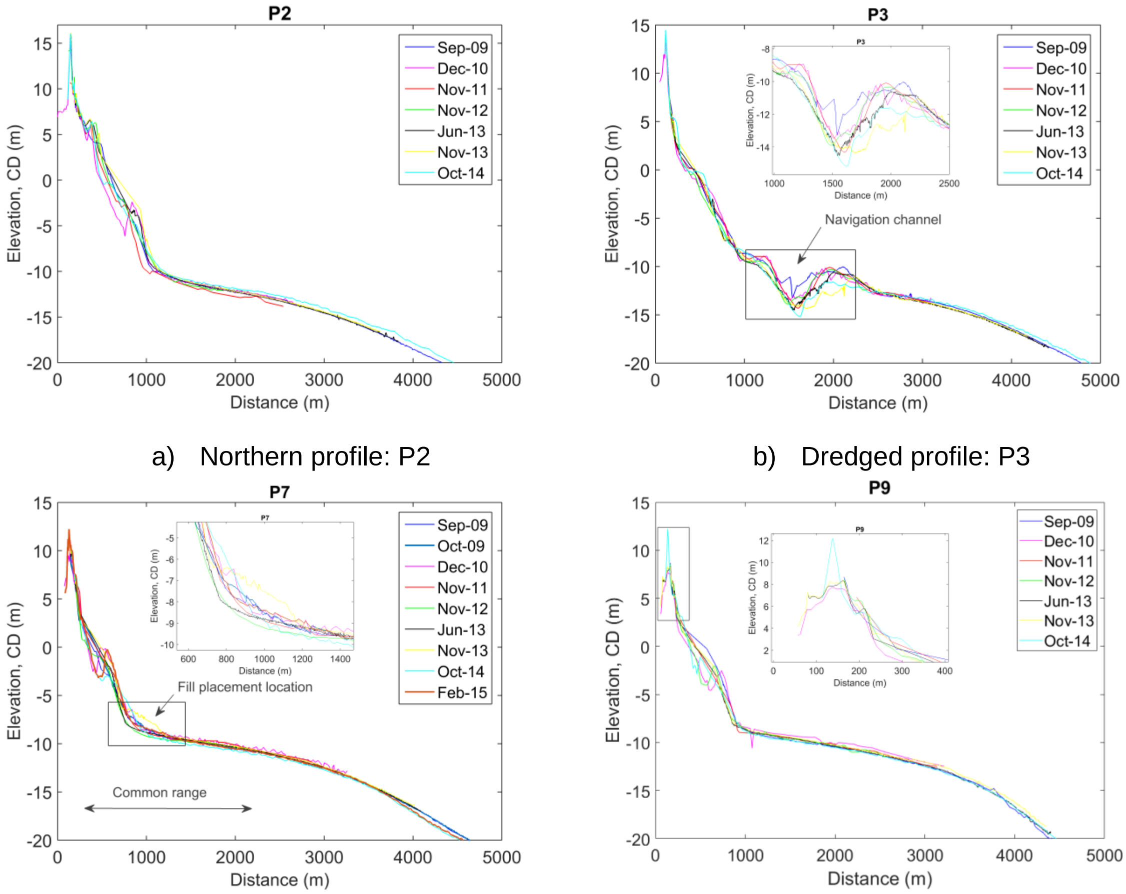
The temporal resolution of the surveys implies some limitations as to what the data can provide regarding analysis and model application. Due to lack of data covering the detailed beach response to seasonal or storm wave conditions, they are not appropriate for analyzing coastal evolution induced by variable forcing conditions. Instead, the present study focuses on the general evolution pattern at the inter-annual scale and the related sediment transport at the study site.

4.2. Methodology

The set of data collected in the field was employed to study the morphodynamic evolution of Barra-Vagueira coastal stretch between 2009 and 2015. First, cross-shore profile variability is discussed, followed by the general evolution of the dumping areas through the use of GIS techniques and EOFs. Morphologic changes, evolution trends, sediment budgets, and fill responses in a short- to long-term perspective within the dumping areas are analyzed.

4.2.1. Cross-shore profile analysis

The understanding of the characteristic scales in time and space of the beach profile behavior has direct applications in coastal engineering projects, including beach nourishment design and the siting of coastal structures (Larson and Kraus, 1994). For S. Jacinto-Vagueira coastal stretch, profile data are available from Sep-09 to Feb-15 and are here used to characterize the beach profile evolution following the implementation of the nourishments. Figure 4.6 displays the surveyed profiles for four transects representative of the updrift region (P2), dredged and nourished areas (P3 and P7, respectively) and the southern stretch (P9).



a) Northern profile: P2

b) Dredged profile: P3

c) Nourished profile: P7

d) Southern profile: P9

Figure 4.6. Surveyed cross-shore profiles for representative transects of the updrift region (P2), dredged and nourished areas (P3 and P7, respectively) and southern region (P9).

Although the quantification of beach change was limited by data constraints linked to the temporal and spatial resolution, behavior patterns could be distinguished through the analysis of a number of striking differences and similarities in the beach topo-hydrography, observed in the *in situ* surveys. Temporal profile variability was first examined for a general understanding of the spatial and temporal scales of the recorded beach profile change. Then, individual morphological features related to the beach shape, such as dune, shoreline position, longshore bars, and nourishment schemes were analyzed. The shoreline position was set as the MSL (approximately the pivot point of seasonal variations) and its evolution was evaluated based on the field observations. The cross-shore position of the sandbar, here defined as the total distance from the instantaneous shoreline to the bar crest, and the bar volume per unit longshore length (m^3/m) were also quantified. Nourishment migration is discussed based on profile observations together with design specifications.

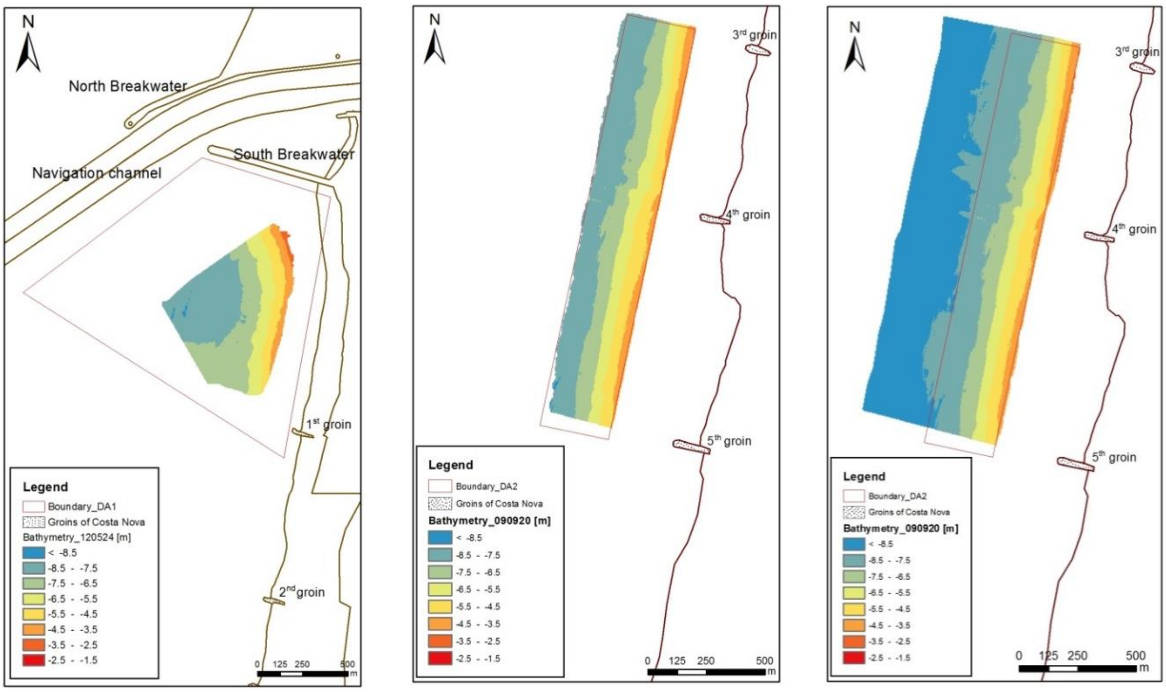
To estimate cross-shore volumetric changes a common range for each surveyed profile was established (see Figure 4.6c). This common range comprises the data region covered by the available surveys. The MSL was selected as the reference elevation to separate the subaerial and subaqueous portions of the beach and sand volumes were calculated per unit longshore length (m^3/m) in relation to the first survey (Sep-09).

4.2.2. Bathymetric analysis

To investigate the morphological response of the dumping areas, a database georeferenced in a GIS (*ArcGis* software) was created from the hydrographic surveys collected by AHA annually, just before and after nourishment operations (Figure 4.7). *ArcGis* tools were applied to determine elevation differences and sediment budgets between surveys. Field data related to the both nourishment areas were processed individually.

Through the use of the '*Raster Interpolation'* tool by *3D Spatial Analyst* extension of the *ArcGis* software, the inverse distance weighting (IDW) method was applied to generate digital elevation models. Since the bathymetric data sets resulting from distinct monitoring campaigns covered different zones, three main areas of analysis, hereafter referred to as the common areas (CA), were defined based on the intersection of the surveyed areas. The first one (CA1), covering 0.43 km^2, corresponds to DA1 and is alongshore bounded by the south breakwater of Barra and the 1st groin of Costa Nova, extending between the water depths 2.5 and 8.5 m (see Figure 4.7a). For DA2, four surveys were identified as presenting short extension and thus, two main common areas (CA2A and CA2B) were established for analysis: one resulting from the intersection of all surveyed areas, with exception of the survey of Jan-14 (which presents the minor area coverage), and another one excluding surveys of Dec-10, Nov-11, Nov-13, and Jan-14. Thus, the second (CA2A) and the third (CA2B) common area (see Figure 4.7b and Figure 4.7c), covering 0.53 and

1.05 km^2, respectively, correspond to DA2 and are both limited by the 3rd and the 5th groin of Costa Nova. In the cross-shore direction, CA2A is limited by the water depths 2 and 9 m (CD), whereas CA2B extends to deeper levels, around -10 m (CD). The reference bathymetry was taken to be May-12 for DA1 and Sep-09 for DA2, each one corresponding to the first survey that was carried out in each area (Figure 4.7).



a) 24-May-12, CA1 b) 20-Sep-09, CA2A c) 20-Sep-09, CA2B

Area=0.43 km^2 Area=0.53 km^2 Area=1.05 km^2

Figure 4.7. Common areas of the bathymetry surveys, for dumping areas DA1 (CA1) and DA2 (CA2A and CA2B).

For each defined common area, sediment volume variations were estimated using the *Functional Surface* tool *('Surface Volume')*. Elevation differences between survey pairs (Table 4.2) were obtained with the *Spatial Analyst tool ('Minus')*, subtracting the interpolated values of two input raster's on a cell-by-cell basis. In cases, where the altimetric comparisons could be extended behind the boundaries of the common areas, enabling a better assessment of the morphological changes of the fills, sediment budgets were also estimated. Surveys carried out just before and after the fill placement were used to evaluate the short-term behavior of the fills, whereas surveys more separated in time were used to investigate the medium/long-term response of the fills (see Table 4.2).

Table 4.2. Bathymetric comparisons undertaken for each surveyed dumping area.

Area	Analysis	Comparisons	Duration
DA1	Short-term behavior	May-12 to Jun-12	One month
		Jun-13 to Jul-13	One month
	Medium-term behavior	Jun-12 to Jun-13	Twelve months
		Jul-13 to Nov-13	Five months
DA2	Short-term behavior	Sep-09 to Oct-09	One month
		Apr-13 to May-13	One month
		May-13 to Jun-13	One month
		Jun-13 to Jul-13	One month
	Medium-term behavior	Oct-09 to Dec-10	Fourteen months
		Oct-09 to Nov-11	Twenty-five months
		Oct-09 to Oct-12	Thirty-six months
		Oct-09 to Apr-13	Forty-two months
		Jul-13 to Nov-13	Four months
		Jul-13 to Sep-14	Ten months
		Sep-14 to Apr-15	Seven months

4.2.3. EOF analysis

Empirical Orthogonal Functions (EOFs) were employed as an attempt to examine spatial and temporal variations of the beach profile shape close to DA2 (Costa Nova beach) on a short- and long-term basis. EOF analysis, also termed principle component analysis (PCA), is a data reduction technique applied to describe the variation of a data set by a small number of independent functions extracted from the data itself (Preisendorfer, 1988; Jackson, 1991). These functions correspond to a statistically optimal description of the data with respect to how the variance is concentrated in modes, where the variance explained decreases with the mode number. Each of these modes of variability comprises a spatial and a temporal component, where the first (lowest) mode explains the greatest percentage of the data variation. In this way, only a limited number of modes are needed to explain most of the variance in the data set. Although the EOF is strictly a data analysis tool with no inherent physical background, physical interpretations are possible in many cases, relating the results of the EOF analysis to morphological features and related physical mechanisms (Larson *et al.*, 1999, Lemke *et al.*, 2014).

A data matrix D (Eq. 4.1) containing, for example, bottom topographies sampled in space (columns) at specific times (rows), may be represented using matrices involving the spatial EOFs (E, *i.e.*, principal components), the eigenvalues L, and the temporal EOFs (A, *i.e.*, principal component scores):

$$D = ELA^T \qquad \text{Eq. 4.1}$$

The column vectors in E and A are orthonormal and correspond to the eigenmodes, and the variance associated with respective mode is given by the eigenvalue in L. The EOFs are usually obtained by solving an eigenvalue problem involving the covariance or correlation matrix based on D, but in some applications the sum-of-square matrix is used instead. In the former approach the arithmetical mean is removed, which is the most common method in applications to morphologic data, because the mean tends to dominate the signal (Larson *et al.*, 1999).

Topo-hydrographic data for four lines (P5 to P8), collected during eight surveys from 29-Oct-09 to 15-Feb-15, were used as input data to the EOF analysis. Linear interpolation was employed to obtain elevations at the same cross-shore locations for all surveys taken at a particular transect. Thus, an input data matrix D(z,t) was constructed, containing rows of elevations surveyed, z, at specific dates, t, in columns. Although the dune behavior could not be described completely by data variation, elevation contours between the seaward dune face (8 m above chart datum) and the depth of closure constituted a good coverage by the surveys.

4.3. Monitoring results

The first part of the analysis focuses on the cross-shore variability of the beach profiles, describing morphological changes linked to dune evolution, shoreline position, bar system, and nourishment behavior, as well as examining volumetric changes (m^3/m of shoreline) for the subaerial and subaqueous portion of the cross-shore profiles (Section 4.3.1). Additional analysis involves the bathymetric surveys targeting the dumping areas and their evolution at two main time scales: short-term and medium/long-term responses of the beach fills (Section 4.3.2). Finally, results from the application of a multivariate statistical method (EOF) to the survey data covering DA2 are presented and discussed (Section 4.3.3).

4.3.1. Cross-shore profile variability

4.3.1.1. General behavior

Maximum variability in elevation of the beach profile is generally obtained between the high water level (+4.0 m CD) and the breaker zone limit (shallow part of the study site). Offshore of this area, changes in profile depth decrease, presenting its minimum around -13 m (CD) elevation contour (Hallermeier, 1978; Birkemeir, 1985; Coelho, 2005). This depth is in agreement with the values discussed in the literature for the depth of closure, where the cross-shore seaward sediment exchange is negligible from an engineering perspective (Coelho, 2005). Landward, where the largest depth variations are observed, changes in profile shape refer mostly to the seasonal variations resulting from processes controlling the erosion and recovery of the dune and berm (see Figure 4.8).

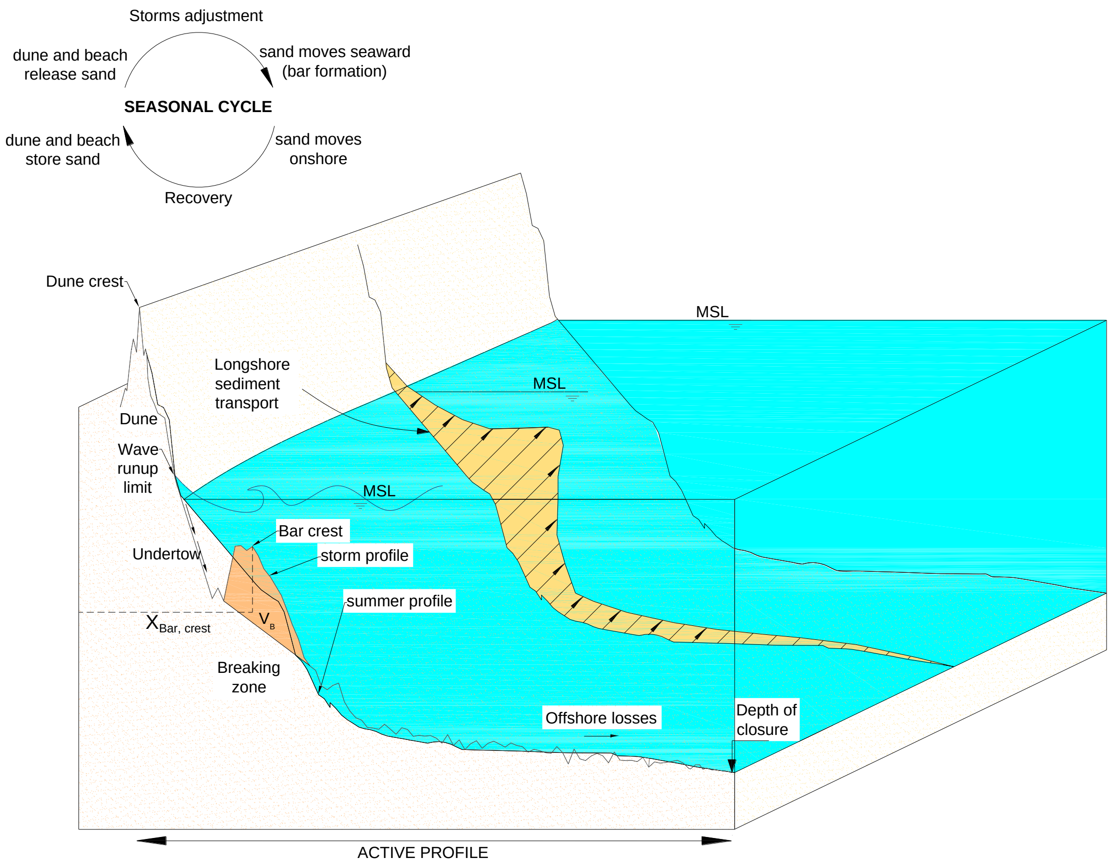


Figure 4.8. Scheme of morphological changes to the beach profile during a seasonal cycle. Definition sketch of bar properties: bar crest, bar volume (V_B) and bar crest distance to the shoreline ($X_{Bar,crest}$).

The northern profiles (P1-P4) show a slight increase in profile bed elevation for deeper areas than -13 m (CD) elevation contour, possibly related to the extension of the northern breakwater, promoting sand accretion for deeper waters on the updrift side of Aveiro harbor and in its protected downdrift area (see Figure 4.6a). The opposite pattern prevails for the most southern profiles (P5-P12). The variability exhibited by the profiles located just south of the Aveiro harbor (P3-P4) seems to be affected by the maintenance operations and natural recovery process of the navigation channel (P3, see Figure 4.6b), together with the diffraction currents generated by the Aveiro harbor breakwaters (P4) and the presence of a nearshore sand shoal (intercepted by P4). Profile P5 shows a particular response, where the measured evolution in time displays significant morphological changes in the subaqueous portion of the profile after 2013. These changes suggest that a large amount of sand in the area defined by the depths -7 and -10 m (CD) moved in the onshore direction forming a nearshore sandbar. Observations from Feb-15, indicate that this sandbar has been driven towards the beach, showing a landward migration of its crest of around 144 m with respect to the Oct-14 survey. In general, the largest variations in the profile shape registered for the southern profiles (P6-P12) are mostly related to seasonal variations.

In Sep-14 and Feb-15, field observations indicated that, in the downdrift area of DA2, neighboring profiles exhibited similar variations in the dune region, revealing an average increase in the dune crest (see Figure 4.6d). This dune growth pattern, recognized south of DA2 along approximately 2 km of Costa Nova beach (intercepting profiles P8 and P9) contributed to the reinforcement of the backshore region of the Costa Nova beach.

4.3.1.2. Shoreline position and offshore bar system evolution

Figure 4.9 presents the variation in shoreline position with time, based on the 12 surveyed cross-sections. As expected, the coastal area along P5-P7 appears to be the region with least retreat in the shoreline position over approximately 5½ years of monitoring, denoting coastline advance mainly after low-energy and nourishment periods. During the storms of Oct/Nov-10, the beach was severely eroded along the entire coastal stretch, resulting in a significant decrease of the beach width observed on Dec-10. The opposite behavior is recorded in Nov-11 and Jun-13 yielding a general advance of the shoreline in relation to the Dec-10 survey. The most seaward shoreline position is observed in Nov-13 along P3-P7, possibly as a response to the fill material dumped in the summer of 2013, in connection with the construction of the northern breakwater. Again, in Oct-14 a general retreat of the shoreline occurs (relative to Nov-13), with an exception to this pattern in the profiles located south of DA2 (P9-P11).

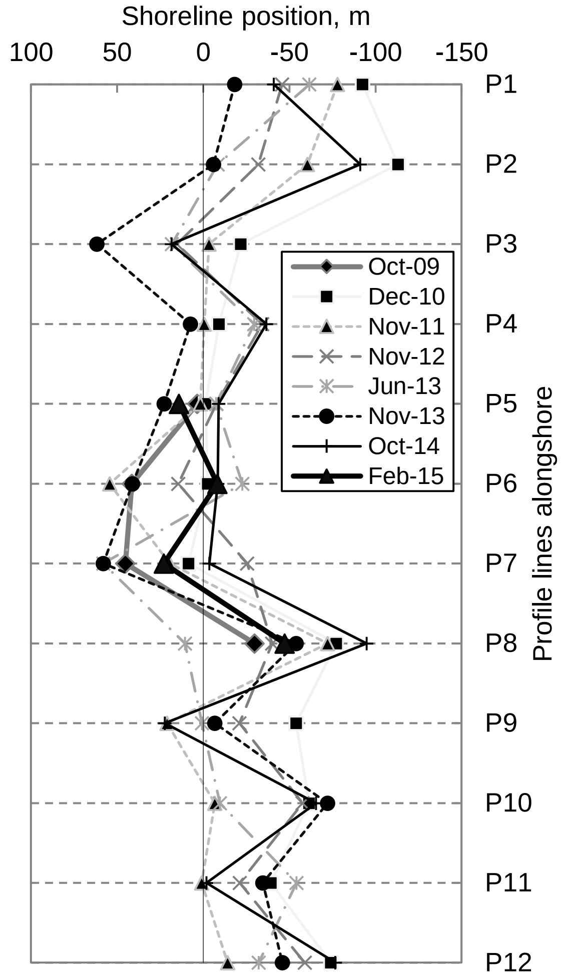


Figure 4.9. Shoreline position (MSL) variation over time relative to Sep-09 shoreline, obtained at surveyed profile lines P1 to P12.

Figure 4.10 displays sandbar volume and distance to bar crest from the shoreline (defined at MSL) for each transect. Overall, profiling has indicated a more frequent presence of the bar southward of P7 compared to the updrift side, where the Aveiro harbor breakwaters and the groin system (located at Costa Nova) are physically affecting the natural flow of the sediment transport and consequently the potential for cross-shore material exchange. The inverse response is observed for the shoreline position evolution: bar appearance (or net offshore bar migration) connected to a shoreline retreat and vice-versa (see Figure 4.9 and Figure 4.10).

In 2010, the presence of a quasi-uniform longshore bar can be clearly identified at an average distance of 346 m from the shoreline, and a sand volume ranging from 266 to 859 m^3/m. As the surveying was carried out during the winter and preceded by two months of high-energy waves (see Figure 4.4), a shift towards a more frequent recurrence of breaking conditions or more intense breaking promoting a larger offshore sediment transport has contributed to this bar appearance. The seasonal change in the wave height, promoting a larger seaward sediment movement is, thus, hypothesized to be the main responsible process for the generalized shoreline position retreat registered during the same period (Figure 4.9). This generalized phenomenon (bar appearance) for almost the whole stretch exalts that this phenomenon is an intermittent process confined to high-energy periods.

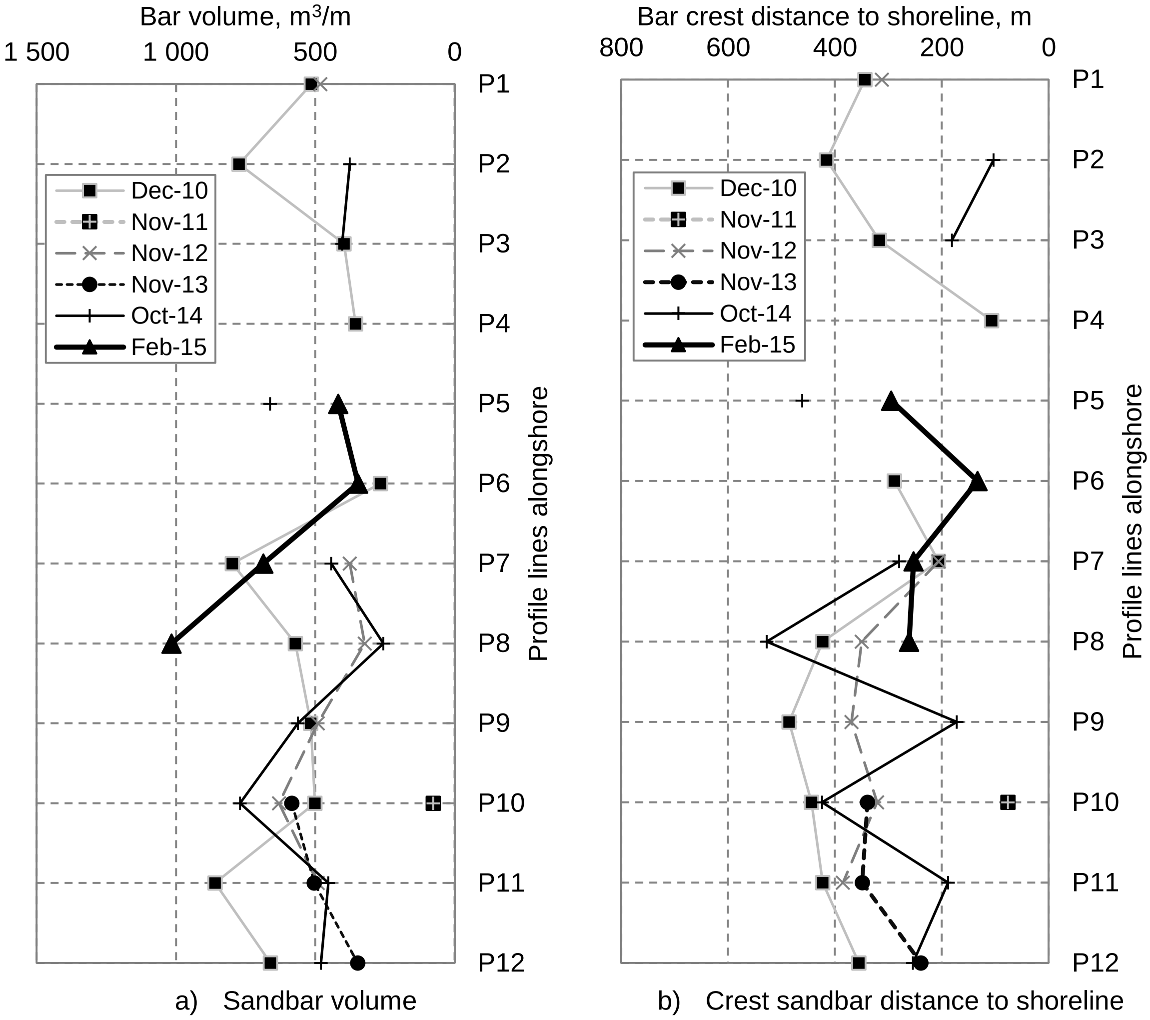


Figure 4.10. Sandbar characteristics (volume and position), along profiles P1 to P12 and over time.

The highest sandbar volume was recorded to be about 1 016 m^3/m, for P8, in Feb-15, with an average crest position located 311 m from the shoreline. This large value is probably partially attributed to the southern spreading of the sand dumped at DA2, which may have helped to feed the bar.

4.3.1.3. Nourishment evolution

Regarding the nearshore nourishment material, only the signal from the large fills carried out at DA2 in Sep/Oct-09 and in Jul-13, could be clearly recognized in the profile data. The absence of detailed topo-hydrographic surveys immediately before and after the generality of the fills prevented the study of the initial process of fill adjustment. However, even without adequate survey frequency, significant changes in profile elevation could be distinguished for P6 and P7 between -6 and -10 m (CD) contours. These changes can be directly linked to the effect of the fills placed in Sep/Oct-09 and in Jun-13, although some cross-shore displacement to offshore is observed in the data (in response to the wave climate). In spite of the lack of frequent data, considering the project specifications for the dumping operations (between -2 m and -7 m CD) and the performed surveys, it was possible to conclude that the large fill material interventions experienced seaward transport, carrying the nourished material to areas offshore of the dumping boundary.

4.3.1.4. Subaerial and subaqueous cross-shore volumetric changes

Figure 4.11 shows the cumulative volumetric changes between Sep-09 and Feb-15 for the entire coastal stretch under monitoring (S. Jacinto-Vagueira, P1-P12). The results in the Figure 4.11 highlight the strong sediment dynamics that take place in the subaqueous portion of the profile: 9 times higher maximum variability compared to the subaerial region. Nevertheless, as the cross-shore width of the subaqueous portion of the profile is much wider than the subaerial, normalized volumes per cross-shore length, m^3/m/m, evidenced a higher average of sediment transport distribution occurring in the upper part of the profile, although its total significance is lower than the subaqueous response. The observations stress the importance of surf-zone hydrodynamic over the time scale studied here that largely shapes this coastal system.

Figure 4.11a displays the subaerial volumetric change, indicating a general sand increase at north (P1-P2) and at immediately south (P3) of the Aveiro harbor and within DA2

(P7-P8). Erosion is noted for P4 and P5, while a stable or slightly eroding area is observed along P9-P11, with P10 being the section that shows the lowest volume variability (maximum value of -90 m^3/m obtained in 2010).

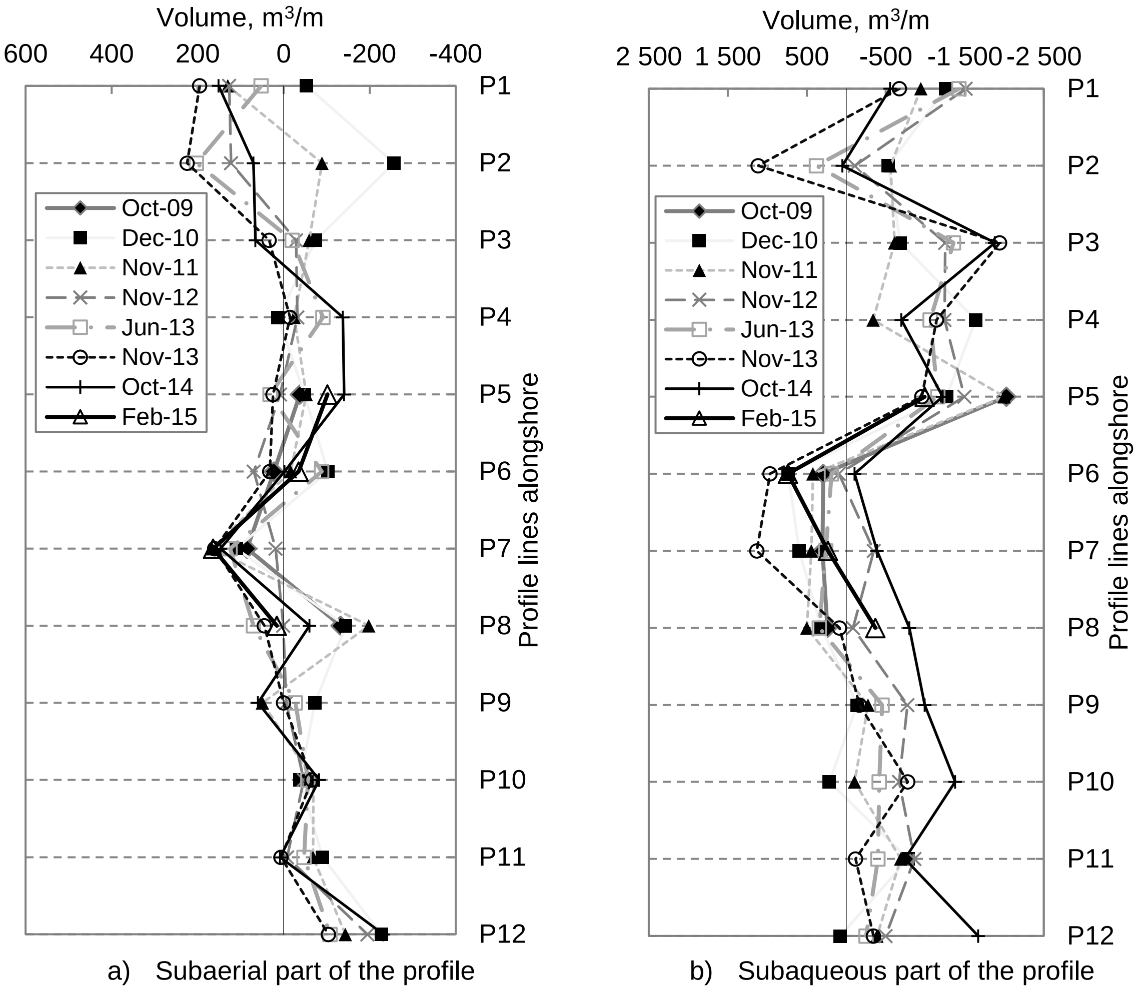


Figure 4.11. Cumulative volumetric changes. Volumes relative to Sep-09 for profiles P1 to P12.

In Dec-10, the beach was in a typical winter state, implying a significant decrease in subaerial sand volume almost everywhere along the coast (except in the neighboring areas of P4 and P7). In general, the beach width was narrow (see Figure 4.9) after large amounts of sand were moved from the dune and the berm to form a longshore bar (see Figure 4.10). In Nov-11, an accreted volume is registered in profiles located just south of the harbor (P3 and P4), possibly due to the high percentage of waves coming from SW during Oct-11. In the summer of 2013, sediment moved back onshore, contributing to the increase of the subaerial beach volume for half of the profiles studied. Contrary, a general volume decrease is observed in Oct-14 for the majority of the profiles (relative to Nov-13), where the erosion in the subaqueous part of the profile for the most southern stretch (P6-P12) is particularly evident. This spatial erosion pattern is probably related to the major storms that hit the study site during Jan/Feb-14 (see the high values of H_s in Figure 4.4). It is estimated that the extremely energetic winter prior to the summer of 2014 was the main cause of the erosion in the surveyed area, leading to an average total sand volume deficit of about 687 m^3/m (sum for the subaerial and subaqueous parts of the profiles).

Below MSL (Figure 4.11b), a highly erosional area can be observed between P3 and P5. For P3, this erosion is mostly governed by dredging operations of the Aveiro harbor navigation channel (see Figure 4.6b) as the largest variations (losses) took place in deeper areas (below the -10 m CD) just after the major maintenance operations (Sep-09/Dec-10; Jun-13/Nov-13). For P5, on the other hand, the largest loss of sediment has been registered between the first and the second measurements, covering a period of only one month. Although it was not possible to identify the potential source of this behavior, the first survey (Sep-09) was considered questionable and has been dropped. By analyzing the behavior at this line with reference to Oct-09 (one month later), the profile registered accretion, benefiting from its position between the two dumping areas. Thus, for the following analysis, the reference survey for P5 was considered Oct-09. The nourished profiles (P6 and P7) are benefiting the most from the sediment added during the periods involving fill operations, whereas profile P2 shows an accretionary trend that can be attributed to the Aveiro harbor breakwater extension (see Figure 4.6a and Figure 4.11b), displaying only a significant volume reduction in Oct-14 (1 063 m^3/m). In Jun-13, a general increase of the subaqueous volume of the beach profile is identified for the entire study site (except in the vicinity of P3). This behavior can be explained by the natural recovery process of the beach (see Figure 4.8), inducing onshore sediment movement and contributing to the beach widening (also in accordance with the subaerial changes, see Figure 4.11a).

4.3.2. Evolution of dumping areas

The responses of the beach fills were put in perspective by comparing chronological sand level changes. The bathymetric evolution of the dumping areas were investigated for short- (just after the fills) and medium/long-term scales (months to years after the fills) by analyzing changes in seabed elevation. Figure 4.12 displays the sediment balance for the dumping areas as a function of time. Figure 4.13 to Figure 4.16 illustrate examples of the short- and medium/long-term evolution observed for DA1 and DA2, respectively.

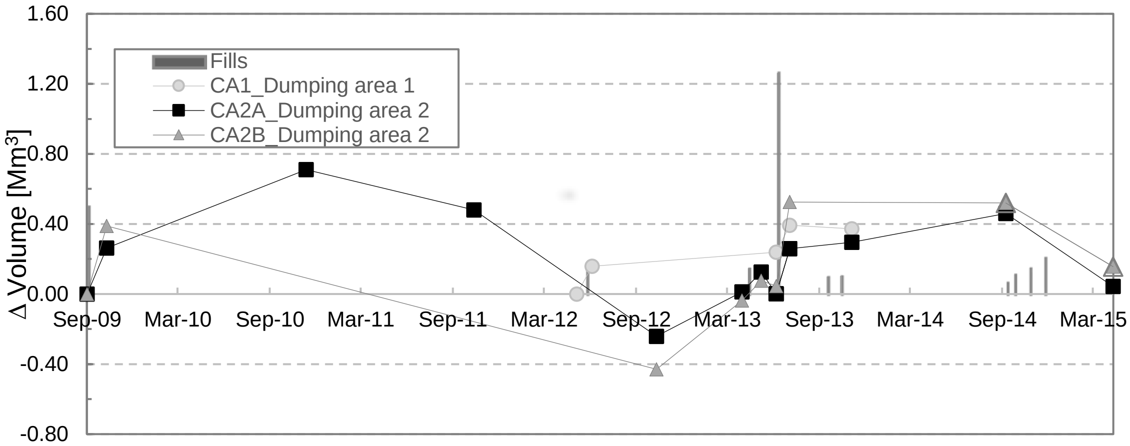
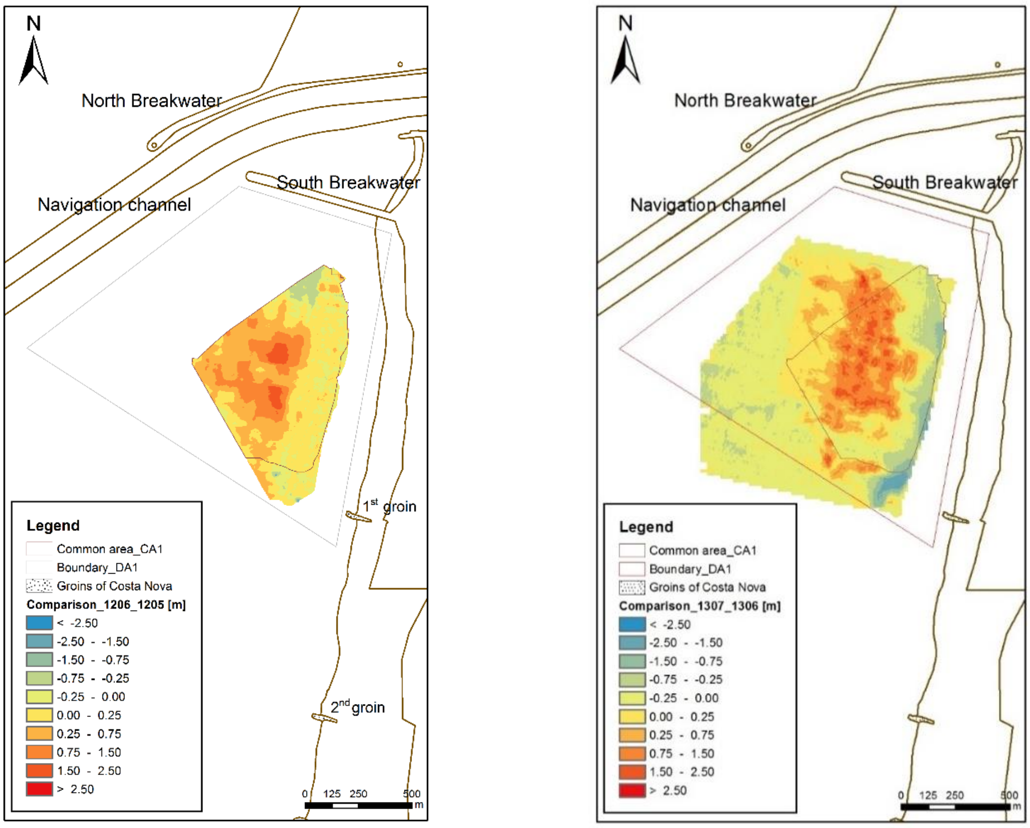


Figure 4.12. Sediment balance for the dumping areas between Sep-09 and Apr-15. The bars correspond to the fill volumes and the symbols (triangles, circles and squares) to survey events.



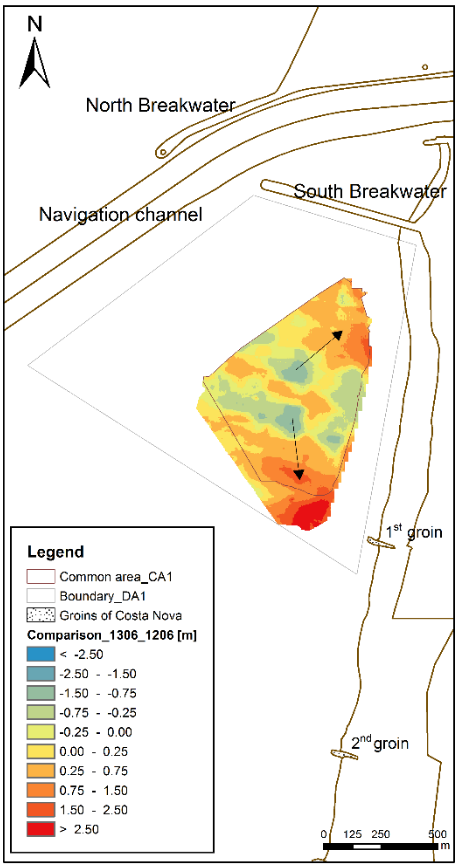
a) May-12 and Jun-12 (1 month)

Area=0.48 km²; ΔVolume=0.16 Mm³
Nourishment volume= 169 218 m³

b) Jun-13 and Jul-13 (1 month)

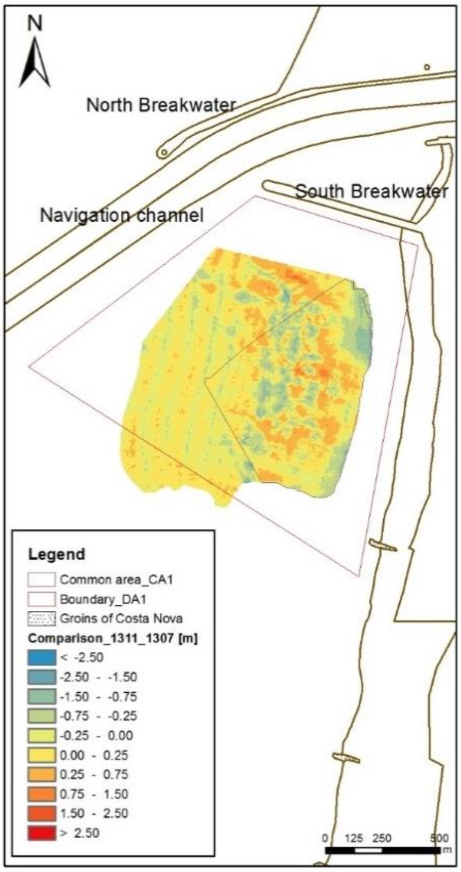
Area=1.11 km²; ΔVolume=0.11 Mm³
Nourishment volume= 251 721 m³

Figure 4.13. Short-term bathymetric evolution at DA1 (bed elevation change between surveys).



a) Jun-12 and Jun-13 (1 year)

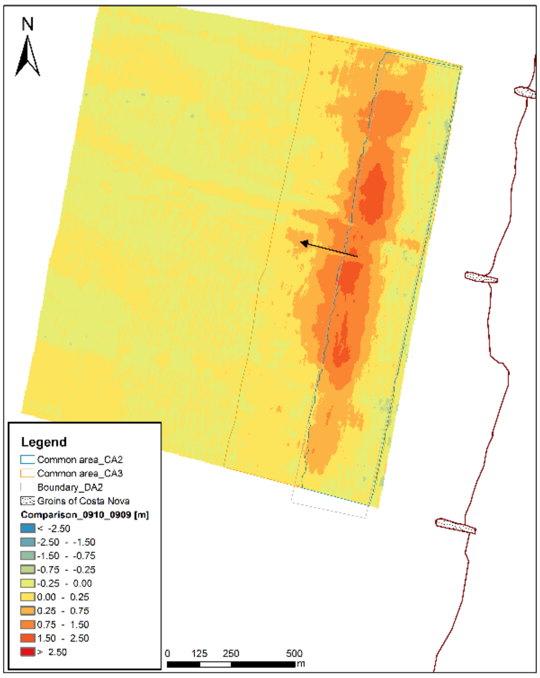
Area=0.52 km^2; ΔVolume= 0.16 Mm^3
Nourishment volume= 79 061 m^3



b) Jul-13 and Nov-13 (5 months)

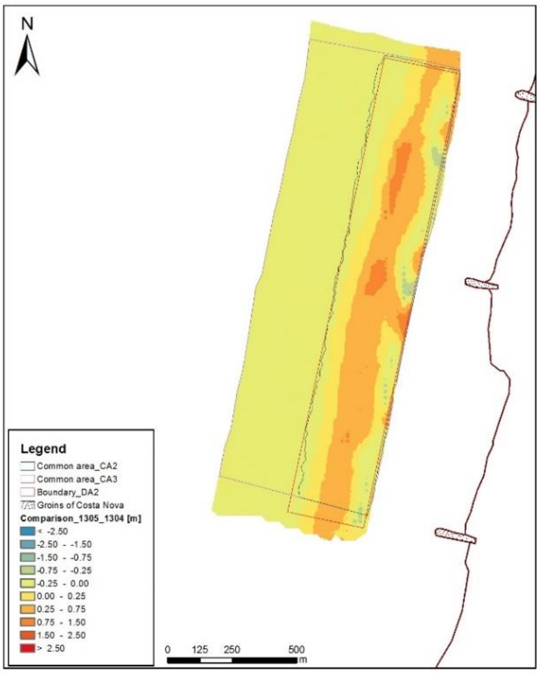
Area= 0.93 km^2; ΔVolume=-0.01 Mm^3
Nourishment volume= 0 Mm^3

Figure 4.14. Medium-term bathymetric evolution at DA1 (bed elevation change between surveys).



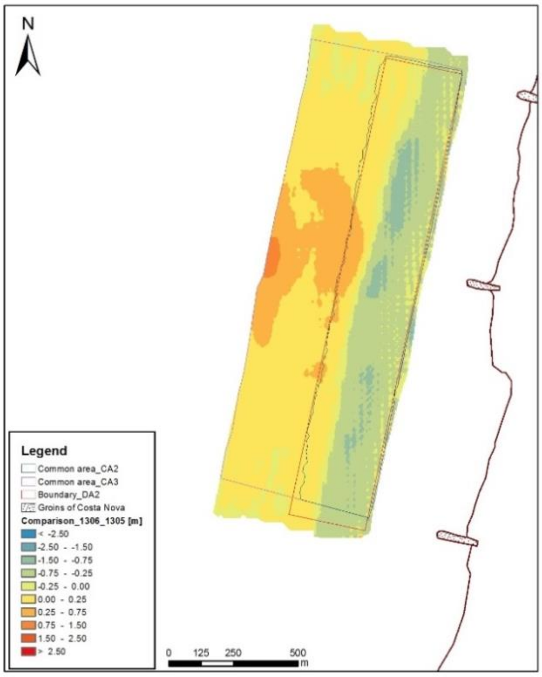
a) Sep-09 and Oct-09 (1 month)

Area=2.52 km^2; ΔVolume=0.36 Mm^3
Nourishment volume= 500 000 m^3



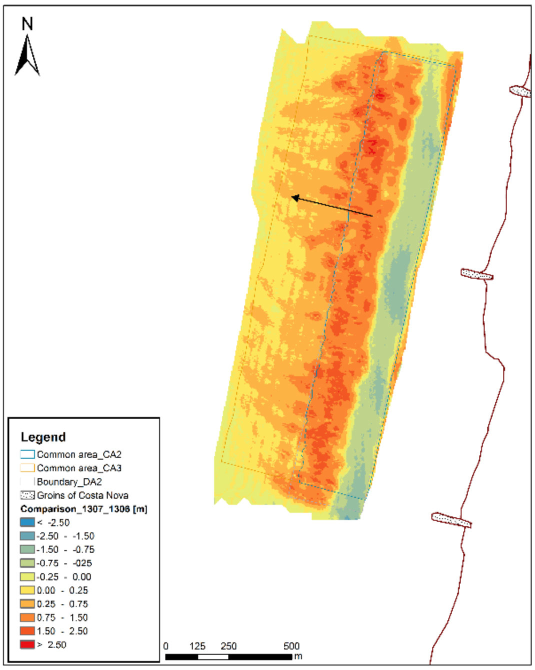
b) Apr-13 and May-13 (1 month)

Area=1.17 km^2; ΔVolume=0.13 Mm^3
Nourishment volume= 66 725 m^3



c) May-13 and Jun-13 (1 month)

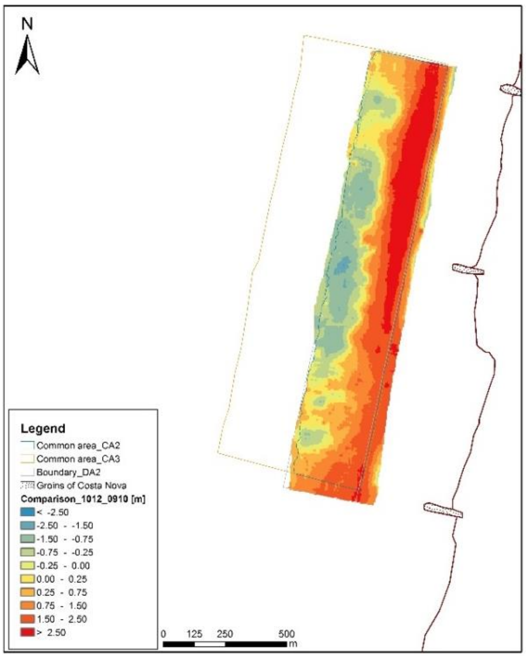
Area=1.17 km^2; ΔVolume= -0.08 Mm^3
Nourishment volume= 0 m^3



d) Jun-13 and Jul-13 (1 month)

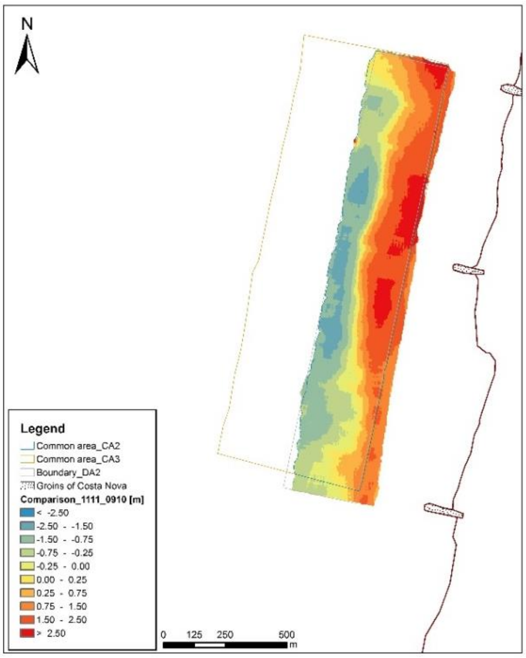
Area=1.30 km^2; ΔVolume=0.50 Mm^3
Nourishment volume= 1 008 113 m^3

Figure 4.15. Short-term bathymetric evolution at DA2 (bed elevation change between surveys). Arrows represent cross-shore material exchange and longshore sediment transport predominant direction.



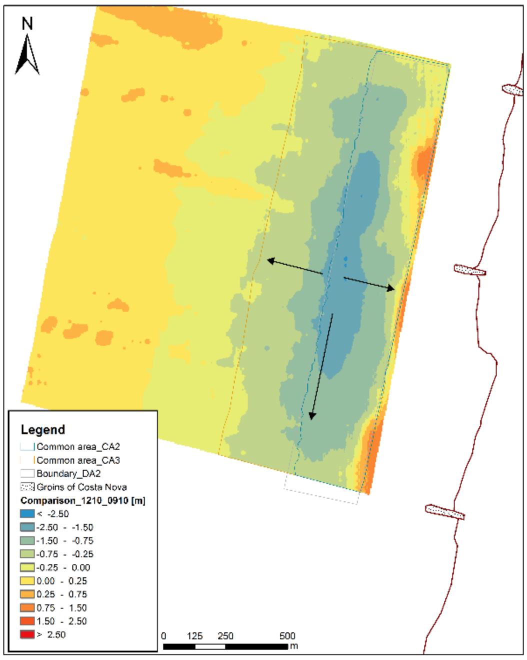
a) Oct-09 and Dec-10 (14 months)

Area= 0.64 km^2; ΔVolume= 0.57 Mm^3
Nourishment volume= 0 m^3



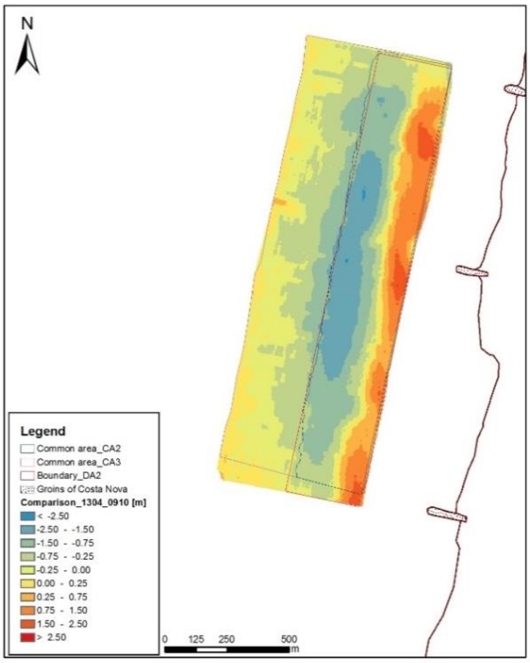
b) Oct-09 and Nov-11(25 months)

Area= 0.61 km^2; ΔVolume= 0.30 Mm^3
Nourishment volume= 0 m^3



c) Oct-09 and Oct-12 (3 years)

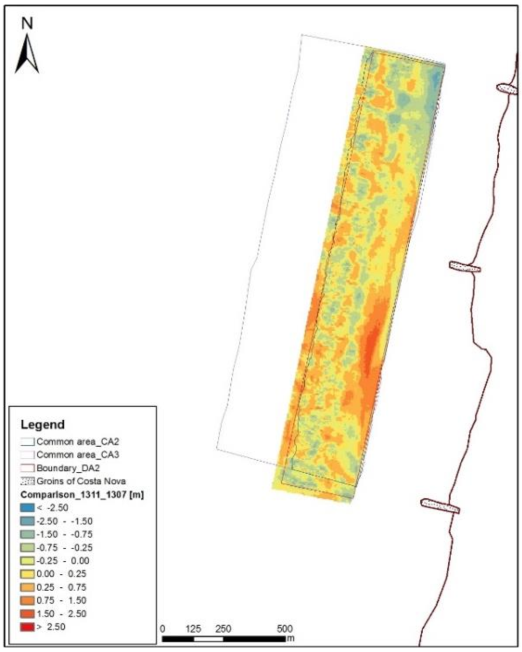
Area= 2.52 km^2; ΔVolume= -0.68 Mm^3
Nourishment volume= 0 m^3



d) Oct-09 and Apr-13 (3 ½ years)

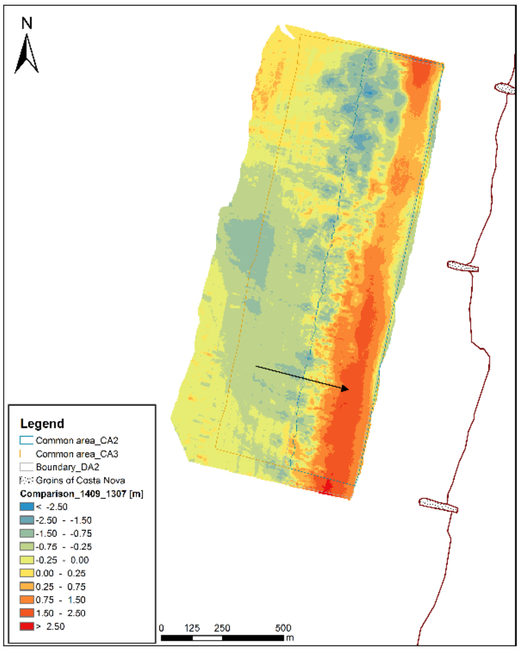
Area= 1.09 km^2; ΔVolume= -0.39 Mm^3
Nourishment volume= 0 m^3

Figure 4.16. Medium/long-term evolution at DA2 (bed elevation change between surveys). Arrows represent CS material exchange and LS sediment transport predominant direction.



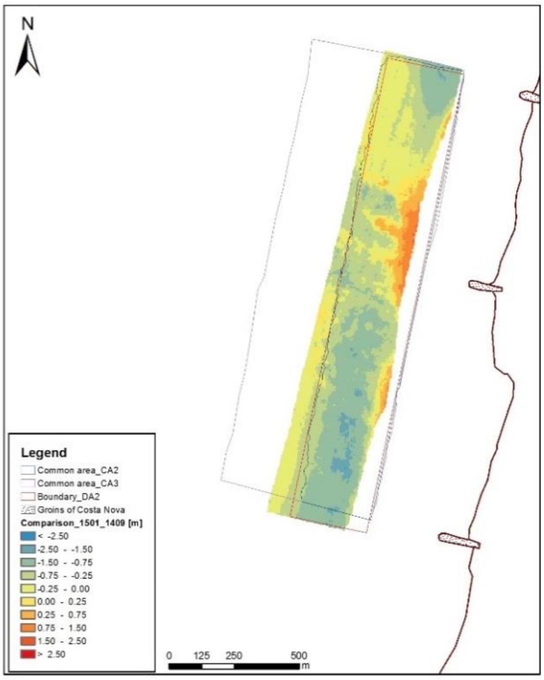
e) Jul-13 and Nov-13 (4 months)

Area= 0.63 km^2; ΔVolume= 0.04 Mm^3
Nourishment volume= 199 297 m^3



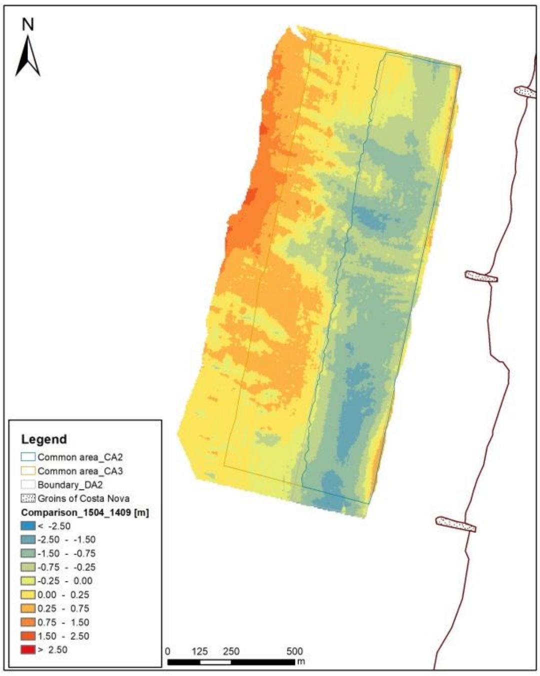
f) Jul-13 and Sep-14 (14 months)

Area=1.40 km^2; ΔVolume= -0.06 Mm^3
Nourishment volume= 199 297 m^3



g) Sep-14 and Jan-15 (4 months)

Area= 0.56 km^2; ΔVolume= -0.25 Mm^3
Nourishment volume= 531 903 m^3



h) Sep-14 and Apr-15 (7 months)

Area= 1.40 km^2; ΔVolume= -0.28 Mm^3
Nourishment volume= 531 903 m^3

Figure 4.16. Medium/long-term evolution at DA2 (bed elevation change between surveys). Arrows represent CS material exchange and LS sediment transport predominant direction – continuation.

The interpretation of the results is performed considering two main viewpoints: short-term and medium/long-term evolution of the sand nourishment in each dumping area.

4.3.2.1. Dumping area DA1

Five hydrographic surveys were carried out, and employed in the analysis, between May-12 and Nov-13, in DA1. The results for the common area (CA1) show positive sediment balances during almost all the periods between surveys, the only exception to this pattern being the period between Jul-13 and Nov-13 (which presents a small loss of 0.02 Mm^3 of sand). To investigate the short-term response of DA1, two bathymetric maps were generated and compared with a time difference between them of one month (see Figure 4.13a and Figure 4.13b). The accretion of 0.16 Mm^3 registered between May-12 and Jun-12 is in agreement with the sand volume dumped in June (169 218 m^3). However, the increase registered between Jun-13 and Jul-13 (0.15 Mm^3) corresponds to only 61% of the nourishment carried out during that period (251 721 m^3), implying that 39% of the dumped material moved out from the surveyed area in one month (Figure 4.12).

Two periods addressing the medium-term response of the fills placed in DA1 were analyzed: Jun-12/Jun-13 (1 year, Figure 4.14a) and Jul-13/Nov-13 (five months, Figure 4.14b). The increase of approximately 0.08 Mm^3 registered one year after the first fill is coincident with the sediment volume that was dumped in May-13 (79 061 m^3). This correspondence of volumes suggests that the material dumped in 2012 (first fill) remained within the common area, although analyses of the surveys shows that the dumped sand has moved alongshore (Figure 4.14a). The sand was transported mostly to the south, although it was also possible to identify some accretion to the north. This particular transport pattern may be related to diffraction and refraction currents generated by the northern Aveiro harbor breakwater, which can invert the sediment transport direction in its shadow area. An erosion hotspot due to divergence in the sand transport is also identified in Figure 4.14a. Between Jul-13 and Nov-13 (Figure 4.14b) an 8% loss of fill material dumped in Jul-13 was recorded. In general terms, the erosion and accretion associated with DA1 decreases and increases, respectively, as the analyzed area is extended (when allowed by available surveys), indicating that the nourishment material remains in the local area, although outside DA1. Between May-12 and Nov-13, the cumulative sand volume change in DA1 was calculated to be 0.37 Mm^3, corresponding to 74% of the dumped material (Figure 4.12).

4.3.2.2. Dumping area DA2

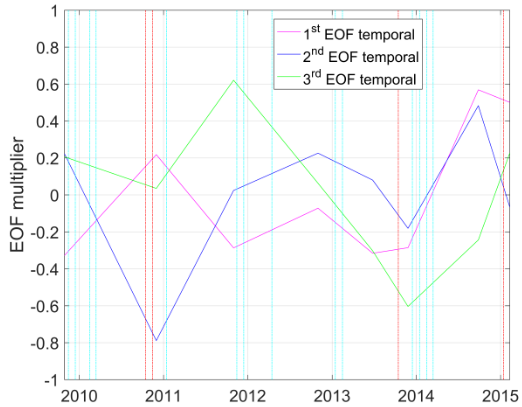
Thirteen surveys were available and analyzed for dumping area DA2. According to the sediment budgets analyses (Figure 4.12), both common areas CA2A and CA2B present consistent behavior, with almost the same trends of erosion/accretion with time. Changes in seabed elevations immediately before and after the nourishment operations (approximately one month) were investigated (see Figure 4.15a, Figure 4.15b, Figure 4.15d). The nourishment mound can be identified by the central darker spots (orange) within the dumping area boundaries (DA2). During May/Jun-13 (Figure 4.15c) and Jun/Jul-13 (Figure 4.15d), there is a clear signal showing a seaward migration of the fill material. The accumulation of sediment obtained for CA2A corresponds only to 67% (Sep/Oct-09) and 53% (Jun/Jul-13) of the sediment accumulation in CA2B, implying that an average of 40% of the dumped material moved out from CA2A in just one month (see Figure 4.12, Figure 4.15a and Figure 4.15d). Also, approximately 51% of the dumped material “disappeared” from the surveyed area between Jun-13 and Jul-13. Here, uncertainties resulting from surveys errors are estimated to be around $\pm$ 105 000 m^3 for CA2B), corresponding to approximately 10% of the fill volume. Two months after the nourishment that was carried out in May-13 (66 725 m^3), there is evidence of offshore transport, with losses around 30 000 m^3 in CA2B (47% of the deposited material).

The results of the bathymetric analyses, ranging from months to several years for DA2 are displayed in Figure 4.16. Until Nov-11, the nourishment eroded (blue) while sand accumulated in the nearshore. The increase of sediment in 2010 is mainly related to seasonal variations in profile morphology, also consistent with the observations displayed in Figure 4.10. The accreted summer profile was eroded by the first storms (note that Nov-10 was a very energetic month, see Figure 4.4), forming an offshore sandbar which lead to a positive sediment budget of around 0.45 Mm^3 in CA2A. Two years after the fill no sandbar was detected (Nov-11). However, cross-shore measurements for P6 and P7 (intercepting DA2) indicated a general profile bed elevation above -6 m (CD) elevation contour relative to Oct-09, which is in agreement with the sand accumulation manifested in Nov-11. Three years later, more than 0.80 Mm^3 of sediments were eroded from CA2B, but approximately 17% (0.14 Mm^3) of the lost sediment in CA2B was stored below the level -9.5 m (CD) - see slight elevation of the sea bottom for deeper areas in Figure 4.16c. The intercepting profiles (P6 and P7) also exhibit a negative sediment balance between Oct-09 and Oct-12 (Figure 4.16c). The negative sediment balance calculated within CA2B between Oct-09 (summer profile) and Apr-13 (winter profile) is around 0.43 Mm^3 (Figure 4.12), which corresponds to approximately half of the change in 2012.

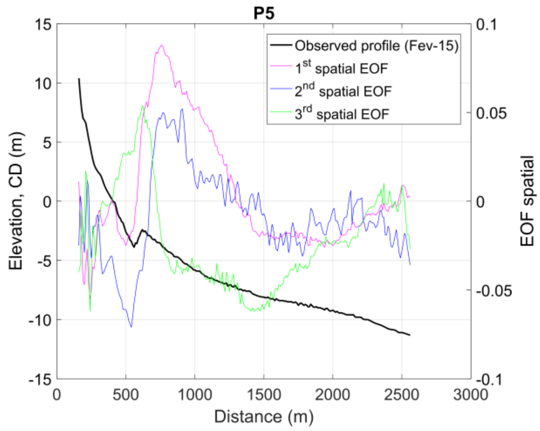
The next fills in DA2 were carried out during May, July, October, and November of 2013, where the second one was the most significant (1 008 113 m^3). In CA2A, comparing the surveys of Jul-13 and Nov-13 (Figure 4.16e), accretion of sand close to 0.04 Mm^3 is observed, corresponding only to 20% of the total nourishment volume dumped in Oct/Nov-13. Extending the temporal scale, the general evolution of the fill placed in Jul-13 can be analyzed between Jul-13 and Sep-14 (Figure 4.16f). During this time, nourishment was carried out only in Oct/Nov-13 (199 297 m^3) and as expected, the dumped material was subjected to the natural adjustment under local wave conditions, which induced a total volume loss around 50 000 m^3 (within the CA2B). As the survey carried out in Jan-15 (after the fill period) covered a small area (Figure 4.16g) a comparison between Sep-14 and Apr-15 was more suitable for investigating the impact of the fills performed during Sep/Dec-14. The sediment budget was calculated to be -0.36 Mm^3, which means that there is no signal from the nourishment volume added (within CA2B). However, Figure 4.16h, suggests that a large concentration of sediments can be deposited outside of the common area boundaries (there is a strong sand accretion pattern that could not be completely represented). The general sediment balance between Sep-09 (the starting survey date) and Apr-15 in CA2B is approximately 0.15 Mm^3, which corresponds to 7% of the total dumped sand volume (about 2.3 Mm^3 of sand). However, these values are clearly affected by seasonal morphological patterns and the fact that the DA2 is located in a very dynamic area, in an open coast exposed to an energetic wave climate.

4.3.3. EOF Analysis

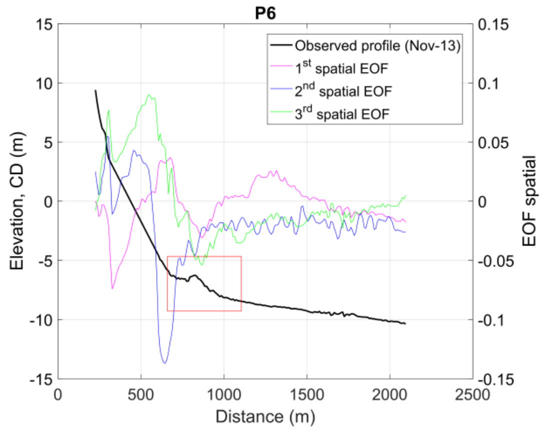
Figure 4.17 shows the main results obtained by the EOF analysis. The data variance, concentrated in eight modes (equal to the number of surveys), drop with increasing mode number. However, only a limited number of modes are needed to explain most of the variation in the data. Therefore, through the first three eigenvectors, 70% of the variation in the data was explained, where the first, the second, and the third EOFs (E_1, E_2, and E_3) contributed 39%, 18% and 13%, respectively, to the total variation. The first three temporal EOFs are displayed in Figure 4.17a (A_1-A_3), and Figure 4.17b to Figure 4.17e show the corresponding spatial EOF maps (E_1-E_3) for profiles P5 to P8, respectively.



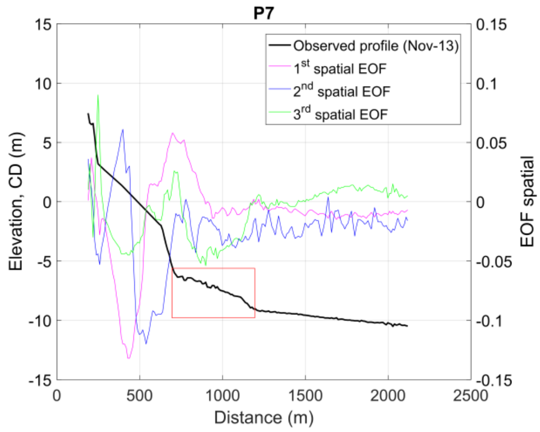
a) First three temporal EOFs (A1-A3). Vertical marks corresponds to the major storms (identified based on the monthly maximum Hs) that hit Costa Nova beach.



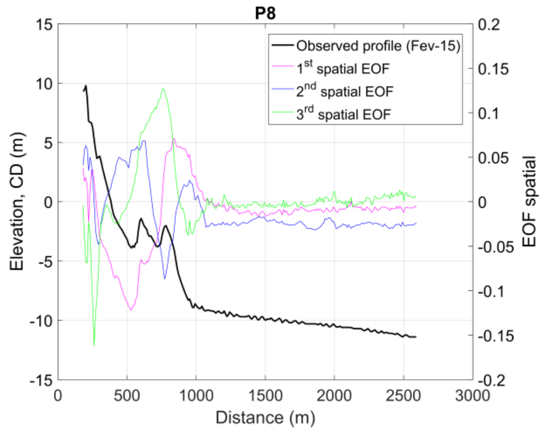
b) Profile P5



c) Profile P6



d) Profile P7



e) Profile P8

Figure 4.17. First three spatial EOFs for each profile around DA2 (data from Oct-09 to Feb-15). Red squares point out the cross-shore location of the fills.

By examining the results presented in Figure 4.17, it stands out that the accretion and erosional patterns described by the first three eigenvectors (see spatial EOFs in combination with the temporal EOFs) are not completely uniform alongshore, indicating different responses from one transect to another. In these cases, a fully straight-forward physical interpretation of the modes is difficult to establish. For instance, by focusing on the behaviors of P7 and P8, the first spatial EOF (E_1) would be interpreted as the exchange of material between the berm and the bar region, which is in accordance with the seasonality manifested by A_1 (Figure 4.17a). A positive value of A_1 would reflect the sediment movement from the onshore to the offshore, where the largest accretion of material (see E_1) typically occurs in about -7 m (CD), with residual changes seaward of this depth. A negative value of A_1 would imply the opposite development: transport from the offshore to the onshore (note that the minimum value is attained in Jun-13, when the beach profile is affected by the summer season). However, the spatial patterns of erosion and accretion highlight a sandy bar appearing during Sep-14 in profile P5, which six months later (in Feb-15) still can be observed. As discussed before, this sandbar is probably a result of onshore sediment transport, promoting nearshore sand accretion. As can be seen from Figure 4.17, locations of accretion and erosion areas for specific profiles in E_1 are highly variable alongshore, P5 and P6 being clear examples of that.

Although the first three modes have explained more than 70% of the variability, the spatial variance found between profiles, which can be mainly attributed to the low spatial and temporal resolution of the cross-shore surveys covering the DA2, prevented the initial process of fill adjustment and storm-induced changes from being identified in the data set. Considering the orthogonality hypothesis between modes, if no physical interpretation could be given to the first mode, which in principal should be alongshore coherent, the subsequent modes (2nd and 3rd) are inevitably affected.

4.4. Discussion

Cross-shore profile data analysis revealed that seasonal cross-shore exchange of sediment volume can exceed the total nourishment volumes. Thus, the artificial bar was not visually detected (as an identifiable feature) in the cross-shore surveys immediately after the first winter, indicating that the fill material has suffered a significant cross-shore distribution. In general, the field measurements collected during more than 5 years of monitoring demonstrated large cross-shore beach variability induced by strong seasonal cycles, large short-term changes of the fill material in the dumping areas, and a generalized erosion trend primarily determined by local wave conditions and a negative longshore sediment transport balance.

As opposed to the northern profiles, intercepting Barra beach, the similarity between temporal cross-shore changes for the most southern profiles (Costa Nova and Vagueira beach, P7-P12) indicate rather uniform behavior and coherence in terms of cross-shore material exchange. The shadow effect of the Aveiro harbor breakwaters, acting as protective barrier, maybe a reason for the different behaviors, interfering with the natural response of the profiles located just south of the breakwaters (P3-P6). In addition, between Jun/Jul-13, under the same wave conditions, at Costa Nova beach (Figure 4.15d) the fill material seemed to suffer a more rapid distribution, dominated by offshore directed currents than at Barra, which during certain periods showed a non-uniform sand distribution, induced by diffraction currents generated by the northern breakwater. As the surveyed dumping regions were relatively limited, significant amounts of sediments were transported across their boundaries in both the longshore and cross-shore directions between surveys. Sand volumes arising from the Barra nourishments may have been driven by longshore transport towards the southern beaches (Costa Nova). However, the influence of the cross-shore material exchange seems to be greater than that from longshore transport gradients in controlling the sediment budgets in the dumping areas. This was also concluded by Park *et al.* (2009) when examining the evolution of the nourished beaches in northeastern South Carolina, USA. Although the cross-shore transport gradients and exchange of material may be larger, in absolute terms, than the material moved due to longshore transport gradients, the former transport often implies no net change within the profile, whereas the latter cause losses or gains of material resulting in erosion or accretion, respectively. Thus, in the long-term, the longshore transport often determines the ultimate fate of the fill.

Over the 5 years of surveying (2009-2014), an average beach profile volume change of 706 m^3/m were eroded from S. Jacinto-Vagueira coastal stretch, while approximately 3 Mm^3 of sand was dredged and dumped on fifteen occasions. The magnitude of the errors arising from the cross-shore surveys, mainly in the intertidal zone, is poorly known because limited measurements were available. Also, it should be stressed that the findings of this analysis have to be considered with care, as the uncertainties related to the accuracy of the elevation measurements can reach 10 cm, which may imply an error in the calculations of sediment budgets ranging from $\pm$ 43 000 to $\pm$ 105 000 m^3, depending on the common area considered (0.43 km^2 for CA1 and 1.05 km^2 for CA2B). Regarding the profile volume changes, the influence of the decimeter accuracy (surveying error) for the subaerial portion is estimated in 20 m^3/m, representing 10% of the subaerial changes (ranging between ± 200 m^3/m), whereas for the subaqueous portion is around 245 m^3/m (16% of the maximum observed volumes variations). Although terrestrial techniques (RTK GPS) are typically between 1 and 3 cm accurate vertically, in the present study the surveying accuracy was considered larger, on the order of magnitude of airborne surveying methods (such as photogrammetry and LIDAR) and video camera systems, which are mainly used when larger areas need to be covered (Blossier *et al.*, 2017).

Areas around the profiles intercepting DA2 showed a final positive sediment balance (according to the last survey conducted in Feb-15) as well as the neighboring area around P2 (in Sep-14). This positive effect for P2 occurred simultaneously with the extension works of the Aveiro harbor breakwater (completed in 2013), whereas the accretion verified for P5-P7 is directly associated with the fills. Between Nov-13 and Sep-14, significant erosion along the entire monitored coastal stretch was observed. During the severe winter of 2013/14, with major storms hitting the study site, the average cross-shore eroded volume for the 12 profiles increased from 19 m^3/m (survey just before) to 706 m^3/m (first survey after).

Despite the significant nourishment volumes (in total more than 2 Mm^3 of dumped sand during 2013-2014), after the first winter (bringing the first storms combined with high water levels), the nourishments could not be detected in either the cross-shore sand volumes or at the dumping locations. Because the material was dumped as nearshore deposits in the subaqueous portion of the profile, where the sediment dynamic is much stronger (Karunarathna *et al.*, 2012), substantial offshore losses occurred, such as the one verified during Jun/Jul-13 at DA2 (approximately 50% of the fill material), even though the sand nourishments were mostly carried out in the summer.

A clear evidence of the dune system reinforcement was observed *in situ* through a significant elevation increase of the dune crest between Sep-14 and Feb-15 for P7, P8 and P9. It is possible that the sand nourishments, carried out on the subaerial beach during the summer of 2014 (not evaluated here), may have contributed to this reinforcement. It is estimated that fills performed on the subaerial beach in late summer, when the berm width reaches its maximum, may stay in subaerial beach profile longer, as suggested by Yates *et al.* (2009), when studying fill behavior at a southern California beach, USA. However, the results of different nourishments schemes and timing of placement on sandy beaches with strong cross-shore fluxes, arising from intense seasonal cycles, are still poorly understood (Yates *et al.*, 2009; Jacobsen and Fredsoe, 2014; Marinho *et al.*, 2017b).

Although EOF analysis is regarded in many cases as a powerful tool for analyzing complex spatial and temporal morphological beach changes (Larson *et al.*, 1999), here, the limited temporal and spatial coverage of the profile dataset have prevented the detection of spatial patterns in a short and long-term basis, leading to a set of physical meaningfulness modes.

Extended spatio/temporal analyses of monitoring data were performed, but several uncertainties remained, pointing out the importance of monitoring programs adjustments at different levels, according to the intended analysis. Still, some typified behaviors could be identified. The main limitation of the analyses performed was the lack of a more systematic and comprehensive monitoring campaigns undertaken *in situ*, preventing the tracking of the nourished sand and consequently restricting a better assessment of the physical processes responsible for the sand distribution in the cross- and longshore direction. Given the uncertainties associated to the measuring accuracy, these were also considered a limitation.

4.5. Summary

In this chapter, GIS techniques and EOF analyses were employed as the main tools to investigate a monitoring data set of the morphodynamic evolution of Barra-Vagueira coastal stretch in connection with several beach fills. Beach topo-hydrography surveys at 12 cross-shore profiles, distributed evenly along the study site, as well as detailed bathymetric data collected in the dumping areas before and after nourishment operations, were available. Of the 12 profile lines (see Figure 4.2), two lines were located north of the Barra inlet (P1-P2; accreting beach) and 10 lines were located south of the harbor, covering the Barra-Vagueira coastal stretch (P3-P12; eroding beaches). Dredged sediment was deposited in two areas: DA1 and DA2 (containing profiles P6 and P7).

Profile observations collected over more than 5 years of monitoring suggested a larger influence on the beach evolution from the seasonal cycle of cross-shore material exchange than from the nourished sand (after the first winter, the fill material could not be detected). The storm surges, that commonly hit the study site, make it liable to large topo-hydrographic changes with immediate impacts on the cross-shore sediment transport and marked effects on the sediment budgets. The most critical period, revealing a widespread erosion, was recorded during the energetic winter of 2013/2014: the average cross-shore eroded volume for the entire study area increased from 19 m^3/m (survey just before) to 706 m^3/m (first survey after). This behavior was also recognized when evaluating the short- and medium-term responses of the fills in dumping areas, revealing a pattern of offshore-directed losses. This implies that the cross-shore material exchange, also identified during periods of low-energy waves, is an important controlling factor for the sediment budget in this coastal system.

Also, profile evolution indicators and bathymetric data analysis lead to the conclusion that the nourishments carried out at the study site had a positive influence on the beach, showing a larger efficiency for the most nourished area (DA2). Despite their small-scale effects, correlated analyses suggested that southern neighboring areas may be benefiting from fill material, confirming the feeding behavior of the nourishments (as evidenced from profile P5 and DA1 evolution).

Although it was possible to associate some changes in the beach morphology to the hydrodynamic forcing events, fill placements, and some sediment transport mechanisms, the limited set of conclusions drawn in this chapter highlights that the monitoring strategy established in DIA falls short, compromising the follow-up studies and an accurate judgment of the project performance. For revealing patterns in data sets on beach morphology that are spatially and temporally sparse, the application of EOF analysis proved to be a weak tool, highlighting the importance of better quality data to achieve adequate evaluations.

Evaluation of how the nourishments have been responding on short-term basis, but especially in a long-term perspective, or how the disposal activities of the dredged material have contributed to alleviate or minimize the erosion trend southward of the Aveiro harbor, still remains unanswered, raising the question about the suitable approach for surveying. A lesson to be learned from this case study, which can be also valid for meso-tidal beach environments, is that a more systematic monitoring plan and comprehensive data collection should be established. Equally important is that highly accurate electronic surveying instruments, in order to collect high-density data accurately and efficiently within a selected time, should be used for supporting future beach management processes. Regular surveys throughout the year, including prior to dredging and periodically thereafter, will help capturing important cross-shore changes (such as the initial adjustments of the fill) and establishing a solid baseline for investigating fill responses, regarding time evolution and performance with a high level of confidence. Contingency plans for collecting surveys immediately after storms should also be included, so that post-storm conditions of the project and storm-induced beach changes may be documented.

Extending the monitoring of the dumping areas, not only in the cross-shore direction (landward/seaward) but also alongshore, is encouraged for a better assessment of the beach fill functionality. A higher spatial resolution of the surveying will also help to obtain detailed insights into the governing processes and the forcing conditions that determine the fill evolution, offering means of attempting to maximize the potential of nearshore accretion and providing a basis for developing guidance for engineers and planners regarding the best practices for fill placement. Future monitoring would benefit from site inspections concurrently with the profile surveying, describing any relevant information that could characterize the subaerial beach state (*e.g.*, evidence of movement of the fill material, dune foot position, unusual erosion or accretion, presence of dune or berm recovery signs, vegetation level, effects of storms such as scarping or overwash) as a way to support the campaigns *in situ*. In conclusion, this chapter serves to stress the great significance of developing a systematic data analysis as part of the monitoring activities, in order to provide tools for identifying problems as well as developing or re-adapting solutions.

Finally, all the findings highlighted in this chapter back up the importance of developing and validating numerical coastal models, in particular profile evolution models, not only for designing optimized nourishment schemes, but also for investigating fill responses on a short-term and long-term basis. The absence of high-quality and synchronized data sets from laboratories or field is typically overcome through the use of automatic tools able to reproduce in a realistic way the beach change over time and which have proved to lead to successful simulations at other sites. However, the morphological processes as well as the hydrodynamic processes governing the beach change are extremely complex and still beyond the current knowledge to describe in detail. For these reasons, such numerical tools often include a limited set of processes characterized by certain time and space scales. The following chapter introduces in deep, the main principles that form the basis of an innovative cross-shore numerical tool, known as the CS-model as well as the theoretical developments that have been further developed to better take into account the subaqueous cross-shore sediment transport processes as well as the response of feeder mounds, later integrated into that model. This tool has been designed to be applicable at regional and decadal scale, constituting the focus of the following research work.

CHAPTER 5

BEACH PROFILE CHANGE MODEL

Chapter structure

5.1. Numerical modelling limitations and capabilities

5.2. CS-model: model description

- 5.2.1. Dune erosion and overwash
- 5.2.2. Wind build-up
- 5.2.3. Berm-bar material exchange: theory for one-bar system

5.3. Model application: Barra-Vagueira coastal stretch

- 5.3.1. Data
- 5.3.2. Model set-up and calibration
- 5.3.3. Results

5.4. Sensitivity analysis to model performance

- 5.4.1. Methodology
- 5.4.2. Model set-up
- 5.4.3. Results of simulated scenarios

5.5. CS-model: additional settings

5.5.1. Theory for two-bar system

5.5.2. Hypothetical bar equation for nearshore placements

5.6. Summary

5. BEACH PROFILE CHANGE MODEL

The study of the beach morphology change, in a broad sense, encompasses subaqueous and subaerial sediment transport processes induced by the variation of the forcing conditions (waves, water levels, currents and winds) that shape the beach on all spatial and temporal scales (Figure 5.1). In coastal engineering, qualitative and quantitative understanding of beach change is highly valuable and extremely pursued for predicting potential land loss rates or shoreline retreats, which in turn are very important for preliminary design of engineering solutions and selection of optimal action plans. As a matter of fact, in the case of artificial sand nourishments projects, as they do not involve any kind of structure in its pure form, the nourished beach is expected to evolve naturally in response to hydrodynamic forces, producing cross-shore and longshore sediment transport without any major constraints to the system. This behavior contrasts to perpendicular coastal engineering structures, which interrupt the littoral drift, inducing significant perturbations in the sediment balance, or to longitudinal revetments that constrain the shoreline position. Although the effects of gradients in the longshore sediment transport may play a role when determining the long-term fate of the fill material, the larger modifications of the nourished beach are induced by cross-shore processes, which may be affected by characteristics of the fill approach (sediment grain size, volumes, frequency, location of the placement site, etc.).

In last years, in order to explore the positive attributes taken from sand nourishments projects and optimize their design aspects, attempting to maximize benefits and minimize costs, a demand for robust cross-shore models able to properly describe the natural evolution of beach, has been emerging. Mathematical models are considered a valid tool to improve the understanding of the historical long-term coastal evolution and to anticipate how it will change in the future, considering different actions fronts. For this reason, such models have become a path to anticipate the evolution of nourishment interventions, not only on a short-term basis, by quantifying the initial adjustments of the fill during storms (redistribution of the fill material) but also at long-term, by determining their evolution towards a new equilibrium state and their impacts to adjacent shorelines.

Changes on beach morphology can occur at a range of different time scales. Three temporal scales of particular importance for which predictive tools are needed are often associated with short-, medium- and long-term beach responses (see Figure 5.1).

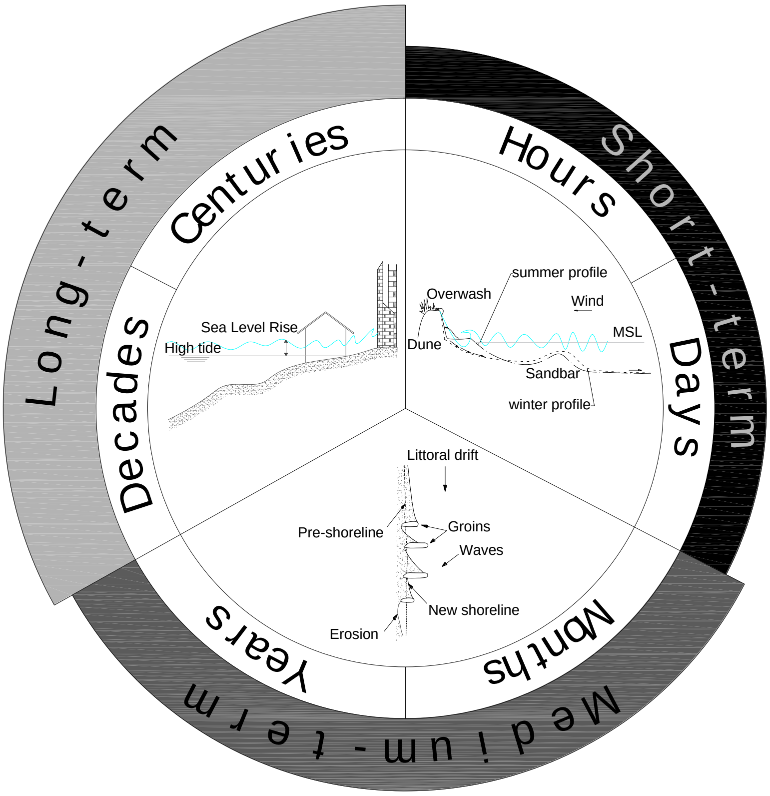


Figure 5.1. Temporal scales of beach morphology change (Marinho *et al.*, 2018b).

The time scale related to short-term processes is often associated with storm-induced beach and dune erosion and occurs in the order of hours to days, depending on the level and duration of a storm event, whereas medium-term responses usually range from several months to a year, depending on the beach seasonality and the surrounding wave climate. Lastly, long-term changes are associated with climate variability time scale (*e.g.* sea level rise) affecting the coastal morphology on order of several decades or centuries (Karunarathna *et al.*, 2012 and Dubarbier *et al.*, 2015). During the latest decade, numerous models have been developed to address these time scales (*e.g.*, Larson *et al.*, 2002; Hanson *et al.*, 2010), with significant progresses given not only at short-term but also at long-term perspective, although inaccuracies of the predicted beach change still remain. While long-term beach change analysis has been employed to predict shoreline evolution based on the potential longshore sediment transport gradient, beach profile evolution has been mostly investigated in a short-term basis. For these reasons, cross-shore (CS) and longshore processes (LS) have commonly been modelled separately, neglecting the three dimensional (3D) effects resulted from the combined action of CS and LS processes, and relying on the engineering judgement to assess it.

Although recent 3D process-based morphodynamic models have been developed in that sense, they are still at early stages of development, and extremely computationally intense. Besides that, in terms of computational costs, it becomes extremely hard combine cross- and longshore effects when the largest morphologic variations on cross-shore direction occur quasi-instantaneously to time-varying, wave regimes whereas the most significance changes on shoreline evolution are reached in a time scale of years or more. Therefore, simplified models of medium to long term changes of beach fronts still provide coastal engineers and managers, helpful guidance at a reasonable effort in terms of computational costs and data requirements for boundary conditions (Karunarathna *et al.*, 2012).

Various types of models have been applied to predict the short-term response of fills (hours to days), but very few models can be applied to estimate long-term cross-shore responses of fills, where the beach moves towards a new equilibrium state (years to decades). In fact, the models that have been more successfully applied for longer time scales often involve the assumption that for given conditions the beach profile will tend to an equilibrium shape, neglecting a realistic seasonal variation of the profile response (Karasu *et al.*, 2008). In more comprehensive coastal evolution models, cross-shore processes can also be represented through source or sink terms introduced in the algorithm, following a schematized approach (Larson *et al.*, 2013).

This chapter introduces a semi-empirical profile evolution model, known as the CS-model, which has been designed to describe the evolution of the beach-dune system at a decadal scale (Larson *et al.*, 2016). This model, firstly presented by Larson *et al.* (2016), takes into account transport processes that act over compatible time and space scales, *e.g.*, cliff erosion and dune recovery, but also short-term processes such as the impact of individual storms, since their effects may be long-term, causing abrupt changes with long-lasting consequences for the beach morphology. In order to model such processes, main morphological features of the profile are schematized and described through a limited set of morphological parameters, where changes in the profile shape are geometrically prescribed by the time evolution of those key parameters. Due to its huge potential, this model has been explored throughout this dissertation with a primer goal to improve its predictive capacity and also to better represent nourishment operations performance, and consequently serve to support the local coastal planning and management. Later in this chapter, the CS-model is applied to Barra-Vagueira costal stretch and targeted to a sensitivity test regarding the performance of distinct artificial sand nourishment scenarios.

Finally, theoretical developments compatible with the calculation approach of the CS-model are presented, introducing new numerical procedures with focus on the evolution of multi-bar systems and the response of feeder mounds which will be later validated in Chapter 6.

5.1. Numerical modelling limitations and capabilities

In support of coastal engineering and management activities, sophisticated, robust, and reliable models for simulating coastal evolution over decades to centuries has been pursued. The earliest type of long-term coastal evolution models focused on predicting the shoreline evolution in response to the potential sediment transport gradient generated by incident wave energy, following the one-line theory. According to this theory, firstly introduced by Pelnard-Considère (1956) and numerically implemented by numerous authors since then, the beach profile moves parallel to itself, maintaining an equilibrium configuration. Thus, one contour line can be used to describe changes in the beach shape and the associated volume during accretionary and erosional events. Some examples of such models are GENESIS (Hanson, 1988), Unibest CL+ by Deltares, LITPACK (LITLINE) by DHI and LTC (Coelho, 2005). Although, these models can be used at large temporal (annual-decadal) and spatial scales (kilometers), one of their weaknesses has been the simplified representation of the cross-shore (CS) material exchange, where usually CS processes are incorporated through sink or source terms, with representative values in time and space.

Profile evolution models, on the other hand, are commonly used to simulate the beach change on a short-term basis (hours to days), for investigating the impact of individual storms in the beach-dune system evolution, as well as the response of beach fills under storm conditions, *e.g.*, SBEACH (Larson and Kraus, 1989), LITPACK (LITPROF) by DHI, XBEACH (Roelvink *et al.*, 2009), but also on a short- to medium-term (month to year) like Unibest TC, by Deltares. These numerical models have been designated as cross-shore profile models, only considering cross-shore sediment transport processes while neglecting any differentials in the longshore direction. During a storm such a simplification is normally of adequate accuracy for engineering applications (Larson *et al.*, 2016; Oliveira, 2015). Nearshore morphology models simulating storm-induced changes have been widely applied for the last decade and demonstrated an acceptable level of accuracy as a result of well-defined cross-shore sediment transport equations, established numerical solutions, and high-quality field and laboratory data (Smith *et al.*, 2017).

The beach-dune system is one of the most important natural coastal protections in low-lying and sandy shores. However, as dynamic natural system, impacts of single storm events (characterized by a considerable rise of the water level and energetic wave heights) can trigger episodes of erosion-overtopping-breaching-flooding, causing irreversible losses for natural environments and adjacent urban infrastructures. Over the last decades, large efforts have been made to predict the impact of these extreme events, through the understanding and analytical reproduction, using numerical models, of the main physical processes involved in the coastal morphodynamic system (Larson and Kraus, 1989; Larson *et al.*, 2013; 2016).

Currently, profile models cannot simulate the beach recovery process on the post-storm scale. So, applying profile response models typically intend to predict beach and dune erosion produced by severe storms or hurricanes, and evaluate initial adjustment of beach fills to wave action and/or fill losses during a storm (Larson and Kraus, 1991). The typical timescale of profile response models is hours to days for a storm event, whereas if long-time beach recovery or fill adjustment is investigated a timescale of months is of interest. For that reason, several model approaches have been developed to address these timescales: models using equilibrium concepts; empirical and semi-empirical models; process-based models (also termed as “deterministic”); behavior oriented models; and data-driven models based on statistical analysis (Karunarathna *et al.*, 2012 and Dubarbier *et al.*, 2015).

According to Larson *et al.* (2016), to improve the predictive capabilities of coastal evolution models, physics-based formulations need to be employed for calculating CS exchange, although schematizations of the governing processes are required to reduce the computational effort. A proper balance between physical descriptions from theoretical considerations and empirical information based on data and observations is the key for simulations addressing large areas and long time periods, that will yield useful simulations results. Larson *et al.* (2013) developed a semi-empirical model to simulate the long-term response of longshore bars to incident wave conditions, as well as the material exchange between the berm and bar region. In this model, the variation in the bar volume is taken to be proportional to the deviation from its equilibrium condition and it is coupled to the berm response (*i.e.*, bar growth implies a decrease in the berm volume and vice-versa). Subsequently, Larson *et al.* (2016) combined this model with modules to calculate dune erosion, overwash, and wind-blown sand (forming a unique-coupled system), in order to simulate the evolution of a schematized profile at a decadal scale. As a first attempt towards modelling regional cross-shore evolution, all of these merged modules gave rise to the CS-model, a cross-shore profile numerical model developed to fill the gap between a sediment budget approach and a detailed profile evolution model. This model has been successfully validated in **Paper I** (Palalane *et al.*, 2016) for several field sites around the world (Portugal, Mozambique and Sweden). The dynamics of selected CS processes were modelled based on physically based expressions, whereas the longshore transport is included in a simplified way through a continuous sink or source applied to the shoreline position. In the following, a short description of each integrated module of the CS-model is provided.

5.2. CS-model: model description

In this section, the cross-shore numerical model (CS-model) will only be briefly reviewed since a detailed description about the theoretical developments can be consulted in Larson *et al.* (2016). This model was developed to simulate the cross-shore exchange of sand and the resulting profile response at a decadal scale by taking into account the main relevant cross-shore processes in a long-term perspective: dune erosion and overwash, wind-blown sand transport, and bar-berm material exchange. Each one of these processes corresponds to an individual module integrated in the CS-model, which contain physically-based algorithms that have been validated against laboratory and field data (Larson *et al.*, 2016).

In order to model the long-term profile response, a set of sand volume conservation equations are employed and solved together with cross-shore transport equations to describe the evolution of key morphological features. These limited morphological parameters are assumed representative of the cross-shore profile and include dune height (s), the locations of the landward and seaward dune feet (y_L and y_s respectively), the berm crest location (y_B), and the longshore bar volume (V_B) – see Figure 5.2. It is assumed that the cross-shore sediment transport, causing changes in the profile shape, is induced by the power of waves and winds, and depends also on the still water levels. These changes, detailing the profile response, are geometrically prescribed so the schematization of the profile type is safeguarded, but the key parameters are changing with time. In the following, a short description about each module integrating the model computations is provided: two modules for calculating the subaerial CS material exchange processes (dune erosion and overwash and wind build-up, Section 5.2.1 and 5.2.2, respectively) and one module for computing the subaqueous material exchange (bar-berm material exchange based on one-bar theory, Section 5.2.3).

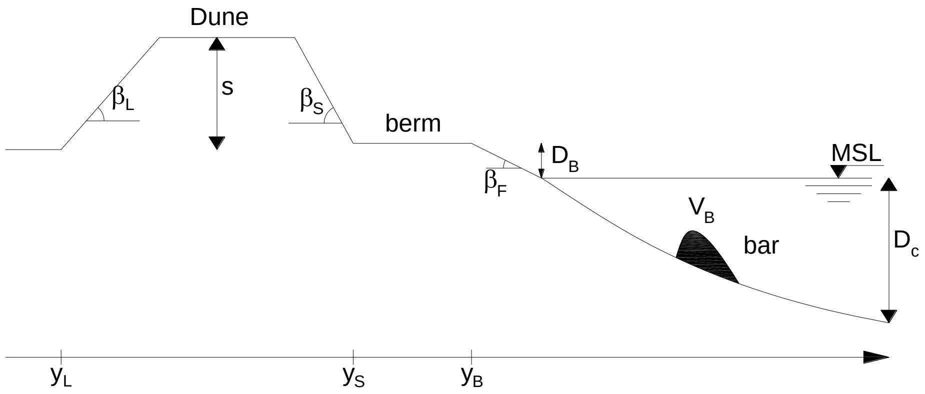


Figure 5.2. Scheme of the profile given by the model. The angles β_L and β_S correspond to the landward and seaward dune face slope, respectively, and β_F to the foreshore slope (constant parameters). D_B and D_C represent the berm height (related to MSL) and the depth of closure, respectively.

5.2.1. Dune erosion and overwash

Dune erosion is computed using an analytical model proposed by Larson *et al.* (2004). This model was developed based on the studies by Fisher *et al.* (1986) and Nishi and Kraus (1996) for dune erosion, where the eroded volume from the dune is taken to be proportional to the impact force from the waves hitting the dune face.

As an example of how the profile may evolve, the impact of a storm is hypothesized. If the waves, together with the water level produces sufficient runup height (R), *i.e.*, if the runup height exceeds the dune foot level, the dune will lose volume (ΔV_D) and supply the beach berm with sand (Eq. 5.1). As a result of this erosion, the dune foot moves shoreward and y_s decreases, assuming that the same seaward dune slope is maintained.

$$\Delta V_D = 4C_S(R - z_D)^2 \frac{\Delta t}{T} \qquad \text{Eq. 5.1}$$

where Δt is the time step of the simulation, z_D the vertical distance between the dune foot level and the water level at each time step (Figure 5.3), T the wave period and C_S an empirical impact coefficient. The smaller z_D the greater the risk of dune erosion. Also, a smaller z_D increases the probability that waves will attack high up in the profile leading to overwash ($R>z_D+s$). In this case, the wave impact is considered to be lower because of the additional momentum flux over the dune (Eq. 5.2).

$$\Delta V_D = 4C_S(R-z_D)s\frac{\Delta t}{T} \qquad \text{Eq. 5.2}$$

During overwash, part of the sediments mobilized by the waves (ΔV_D) will be transported over the dune crest to the shoreward side of the dune (ΔV_L), implying a decrease in y_L (landward movement). In this case, the landward dune face slope, β_L, is also assumed constant. The remaining material will be moved seaward (ΔV_S). The partitioning of ΔV_D between ΔV_L and ΔV_s (*i.e.*, how much of the eroded dune volume goes onshore and offshore, respectively) is given as a function of the ratio α: yielding $\Delta V_L=\Delta V_D\alpha/(1+\alpha)$ and $\Delta V_s=\Delta V_D/(1+\alpha)$.

$$\alpha = \frac{\frac{R-z_D}{s}-1}{A} \qquad \text{Eq. 5.3}$$

where A is an empirical coefficient determined to be about 3 by Larson *et al.* (2009), through comparison with field data. When $\Delta V_D>V_D$ it is considered that the dune is eroded away (Larson *et al.*, 2009).

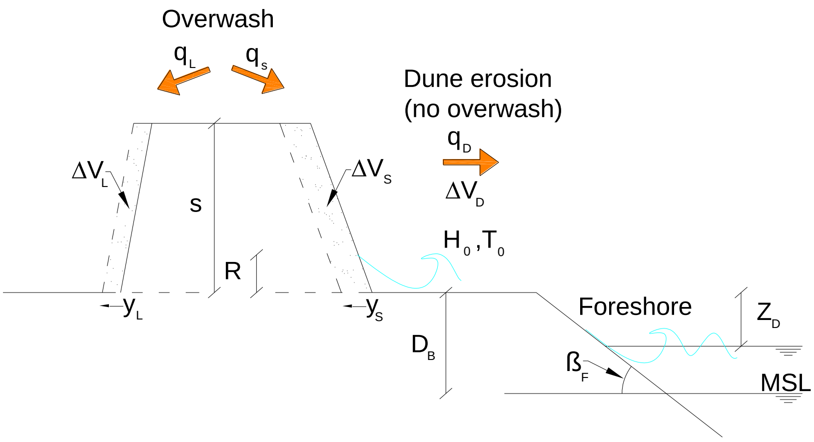


Figure 5.3. Scheme of dune erosion and overwash processes. q_L represents the overwash transport rate and q_S and q_D the seaward transport resulting from erosion of the dune (backwash transport) in cases of overwash and no overwash, respectively.

5.2.2. Wind build-up

Recovery of the dunes depends on the conditions for wind-blown sand (Figure 5.4). Therefore, dune growth can take substantial time and irreversible changes in the coastal system may occur. It is assumed that the aeolian transport rate increases along the foreshore zone, reaching its equilibrium value (potential) after some distance between the shoreline (berm crest) and the dune foot. This equilibrium transport rate (q_{WE}) is computed by using the formula proposed by Lettau and Lettau (1977) which includes the shear velocity and a critical value of the shear velocity that needs to be exceed in order for sediment transport to occur. Also, as the wind blows from the shoreline towards the dune barrier, the equilibrium distance should depend on the local conditions, such as, the dimension and humidity of the sediments and the wind velocity (Hotta, 1984; Davidson-Arnott and Law, 1990). According to field measurements, Hotta (1984) indicated that a distance of 5-10 m would be sufficient to reach the equilibrium state, whereas David-Arnott and Law (1990) reported that 20-30 m (or more) may be required. Here, a heuristic version of the model developed by Sauermann *et al.* (2001) is applied to describe the initial spatial growth of the transport rate (q_W), allowing q_W=0 m^3/s/m at y=0 m (Eq. 5.4):

$$q_{WS}=q_{WE}\left(1-\exp\left(-\Delta\left(y_B-y_S\right)\right)\right), \qquad \Delta\left(y_B-y_S\right)<20 \qquad \text{Eq. 5.4}$$

where Δ is a spatial growth coefficient for the transport rate. Although the model allows for time-dependent wind transport rate calculation, a constant aeolian transport rate (q_{WS}) defining the speed of the dune growth process can also be specified in both the landward and seaward side of the dune (Figure 5.4). This can be useful in the cases that there is no consistent data series on wind velocity and direction.

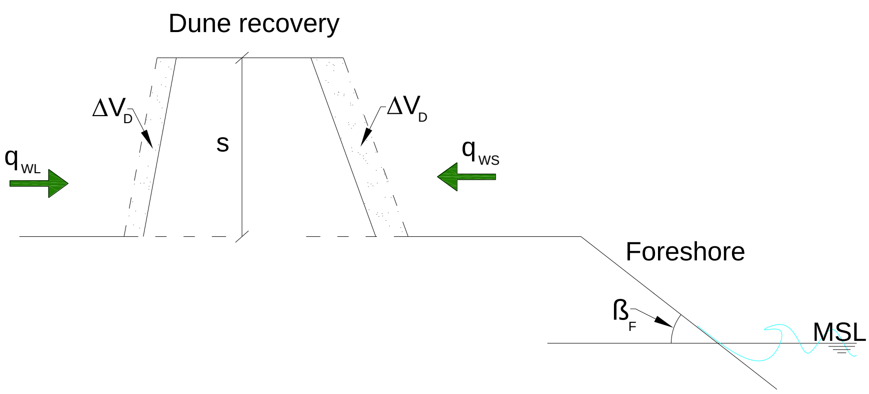


Figure 5.4. Scheme of dune recovery by wind processes. ΔV_D represents the dune volume variation and q_{WL} and q_{WS} to the wind-blown transport on the landward and seaward side of the dune, respectively.

5.2.3. Berm-bar material exchange: theory for one-bar system

In one-bar systems, the volume eroded from the berm is stored in one offshore bar (or, its representative morphological volume) that will reach a certain equilibrium volume (V_{BE}), if the wave conditions are steady and the sediment grain size does not vary (Larson *et al.*, 2013). If the bar volume (V_B) at any given time is smaller than V_{BE}, then the bar volume will grow, whereas the opposite ($V_{BE} < V_B$) implies a decay in the bar volume. Consequently, growth in bar volume causes the corresponding decrease in berm volume (or shoreline retreat), and decay in bar volume causes an increase in berm volume (or shoreline advance). Figure 5.5 illustrates the cross-shore exchange of material between the subaqueous (bar) and subaerial (berm) portion of the profile.

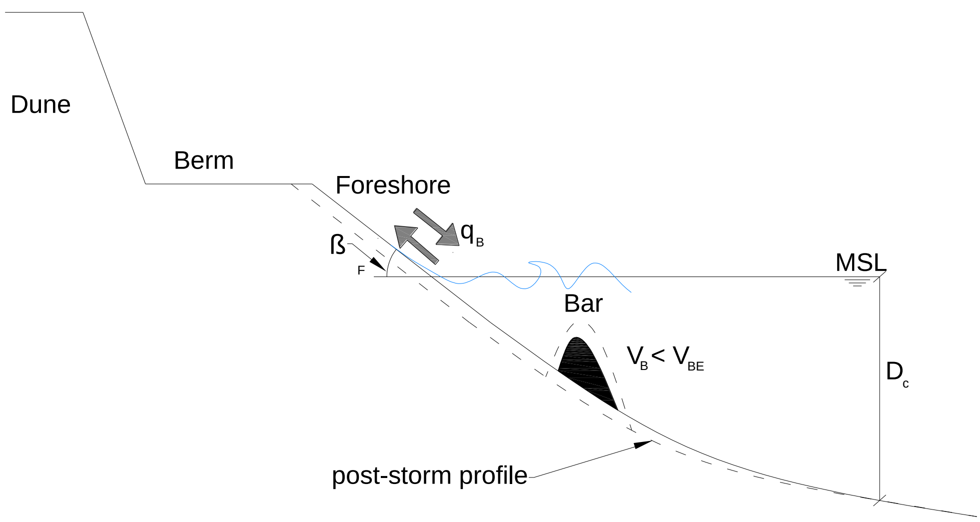


Figure 5.5. Scheme for one-bar theory. The variables q_B and β_F denote the subaqueous transport rate between the bar and berm and foreshore slope, respectively.

The change in bar volume is taken to be proportional to the deviation from its equilibrium value,

$$\frac{dV_B}{dt}=\lambda(V_{BE}-V_B) \qquad \text{Eq. 5.5}$$

in which λ is a coefficient quantifying the rate at which equilibrium is approached. This coefficient depends on the sediment grain size (or fall speed, w), wave height (H_0), wave period (T), and the λ_0 and m coefficients, which should be calibrated against data, according to:

$$\lambda=\lambda_0\left(\frac{H_0}{wT}\right)^m \qquad \text{Eq. 5.6}$$

A representative beach slope is implicitly contained in the fall speed (or grain size) because the equilibrium beach profile depends on this quantity (Dean, 1987). Observations of bar response to storms (Larson *et al.*, 2016) indicate that bars would exhibit a relatively larger growth in the field during energetic wave conditions, whereas the recovery process would be slower (during periods of calmer waves). An additional factor is used to adjust the coefficient λ_0 ($\lambda_0^{on}= C_c^{on}\lambda_0$; $\lambda_0^{off}= C_c^{off}\lambda_0$) when onshore or offshore sediment transport occurs ($V_{BE}<V_B$ and $V_{BE}>V_B$, respectively) as a way to better reproduce the observed bar behavior in the field, defined by a relatively slower response during onshore sediment-transport driving mechanisms (Larson *et al.*, 2016). Larson *et al.* (2016) suggested suitable values for m (=-0.5) and for λ_0 (0.15 h^{-1} and 0.002 h^{-1}) when applying Eq. 5.6 to laboratory and field data, respectively. Qualitatively, a larger value of λ produces a rapid response toward equilibrium. This parameter was also found by Davidson *et al.* (2013) and Splinter *et al.* (2018) to be a key parameter when quantifying the degree of disequilibrium term to express the time-varying position of the shoreline and sandbars.

In order to apply Eq. 5.1, the equilibrium bar volume (V_{BE}) also needs to be determined. According to Larson and Kraus (1989), it is desirable to use non-dimensional quantities to obtain general and physically-based relationships relating morphologic features to wave and sand parameters. Based on large wave tank (LWT) experiments under near-prototype wave and beach conditions (for monochromatic waves), Larson and Kraus (1989) developed an empirically based expression for V_{BE}, where the normalized equilibrium bar volume was shown to depend on the dimensionless fall speed ($\Omega=H_0/\ w/T$) and the deep-water wave steepness (H_0/L_0),

$$\frac{V_{BE}}{L_0^2}=C_B\left(\frac{H_0}{wT}\right)^{4/3}\frac{H_0}{L_0} \qquad \text{Eq. 5.7}$$

in which L_0 is the deep-water wavelength and C_B is a dimensionless coefficient. According to Eq. 5.7, a larger wave height implies a larger bar volume and a greater fall speed (or larger grain size) implies a smaller bar volume (Larson and Kraus, 1989). For more information about the correlation and regression analyses detailing the degree of dependencies between variables consult Larson and Kraus (1989). Larson *et al.* (2016) obtained different values on C_B when applying Eq. 5.1 for predicting bar volume evolution during laboratory experiments and field observations (0.028 and 0.08, respectively).

Considering realistic wave input, Eq. 5.1 has to be solved numerically. For each time step Δt, the wave and sediment properties will be constant (yielding V_{BE} and λ to be constant), and so, the following analytical solution is employed,

$$V_B(t)=V_{BE}+(V_{B0}-V_{BE})e^{-\lambda t} \qquad \text{Eq. 5.8}$$

where V_{B0} is the bar volume at t=0. The bar evolution equation Eq. 5.5 is applied during the growth and decay process of the bar, so, if $V_{BE}>V_{B0}$ the bar will grow (with sediment from the berm) and if $V_{BE}<V_{B0}$ the bar volume will decay (transferring sediment to the berm). Thus, the change in bar volume (ΔV_B) during Δt is given by,

$$\Delta V_{B,i}=(V_{BE,i}-V_{B,i})(1-e^{-\lambda_i \Delta t}) \qquad \text{Eq. 5.9}$$

where subscript i denotes a certain time step. The new volume at time step i+1 is obtained from $V_{B,i+1}=V_{B,i}+\Delta V_{B,i}$. With the knowledge of the initial conditions (V_{B0}) and the input wave conditions, Eq. 5.9 can be used to calculate the evolution of the bar volume, both during growth and decay.

5.3. Model application: Barra-Vagueira coastal stretch

In this section, the CS-model is applied to Barra-Vagueira case study with the purpose to simulate cross-shore beach and dune evolution between 2009 and 2013. The aim is to predict the medium-term response of a cross-shore profile due to the main forcing conditions (waves, water levels and winds), in order to assess the performance of beach nourishments as a measure to control beach erosion and protect adjacent urban areas. The CS-model was set up for Profile P6 (see Figure 4.2), which intercepts the dumping site DA2 and is assumed representative for the studied coastal stretch.

5.3.1. Data

5.3.1.1. Waves

The wave climate characteristic of the study site has been in analysis in Section 4.1.2. Time series of peak period (T_p) and associated directions (θ), significant wave height (H_s), and average of the periods corresponding to H_s (T_{Hs}), with 3-hours intervals, has been selected for the period 2009-2013 and used as input to the simulations (Figure 5.6). During this period maximum and average significant wave height of 8.3 m and 2.0 m, respectively, were observed. The maximum wave peak period was around 18.4 s, with an average value of 9.2 s.

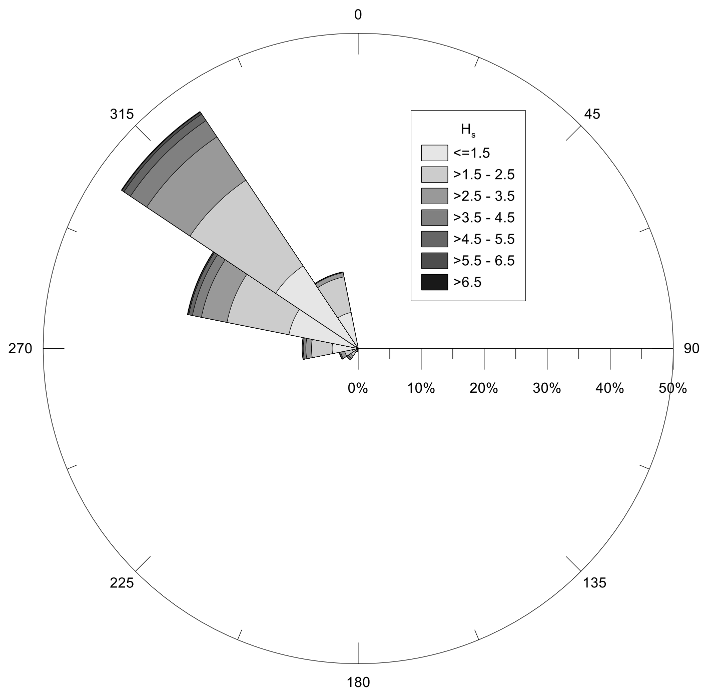


Figure 5.6. Wave rose with energy based significant wave height, H_s, at Leixões (2009-2013).

5.3.1.2. Water levels

Data on tidal projections, available from the Portuguese Hydrographic Institute (IH) for the Aveiro harbor, were used to characterize the still water level between Sep-09 and Nov-13. The projections are calculated based on harmonic analysis of tide gauge observations of variable duration (IH, 2017). Based on projected high and low tide values, a sinusoidal interpolation (Eq. 5.10) was employed to obtain the elevations of Sea Water Level (SWL), in relation to CD, at the same time that wave records were collected.

$$z_t = \frac{H_t + h_t}{2} + \frac{H_t - h_t}{2} \cos \frac{\pi t}{T_t} \qquad \text{Eq. 5.10}$$

where, z_t is the sea water level at the moment after a high or low tide, t is the time interval between the previous extreme tide and the interpolation moment, H_t and h_t are the values of two consecutive extreme tidal projections (before and after the evaluated instant, respectively) and T_t the time period between them (IH, 2017). Based on SWL data available, the mean tidal level is calculated in 2 m water depth (in relation to CD), presenting an average tidal amplitude of 2.04 m and a spring amplitude of up to 3.46 m. The maximum value of high tide occurred on 02-Mar-10 and reached 3.75 m.

5.3.1.3. Interventions

Between 2003 and 2009, several dredging/dumping operations in connection with Aveiro harbor activities have been carried out along Barra-Vagueira coastal stretch. These operations have been discussed earlier in Chapter 4, and taken into account in the simulations through instantaneous increments to the bar volume, since the dredged sand has been placed in subaqueous portion of the profile, around water depths close to the submerged bar location.

5.3.1.4. Sediments

According to the National Information System of Littoral Resources (SNIRL), Barra-Vagueira coastal stretch is composed by beaches with medium to coarse sands in its subaerial region and medium to fine sands in the subaqueous region. In the absence of samples collected in the field to perform a sediment grain size analysis, a median sand grain size, d_{50}, of 0.3 mm was specified. This value is consistent with the study developed by Narra *et al.* (2015) – see Section 4.1.

5.3.1.5. Morphology

As presented in Section 4.1.3, topo-hydrographic surveys for 12 cross-shore profiles covering the study site were made available between 20-Sep-09 and 26-Nov-13 by AHA.

The profiles were surveyed from the top of the dune to a depth of -10.0 m (CD) or deeper, and spaced 1 km each. For the present model application, Profile P6 (see Figure 4.2) was selected, as it is the profile with the highest data quality along the subaerial part of the beach, located closest to the urban areas. This profile, at Costa Nova beach, intercepts the deposition site DA2, which means that was directly influenced by nourishments performed by AHA during the period 2009-2013. Figure 5.7 displays the surveys collected for this profile, as well as the observed position of the landward and seaward dune foot and the seaward berm limit. The seaward dune foot location, y_S, was specified at the dune foot position of the profile where it registered the lowest horizontal variation along time between field surveys (5.9 m above MSL). According to the survey of 26-Nov-13, which presents a very pronounced berm crest, the seaward berm limit, y_B, was specified at a location 4.1 m above MSL.

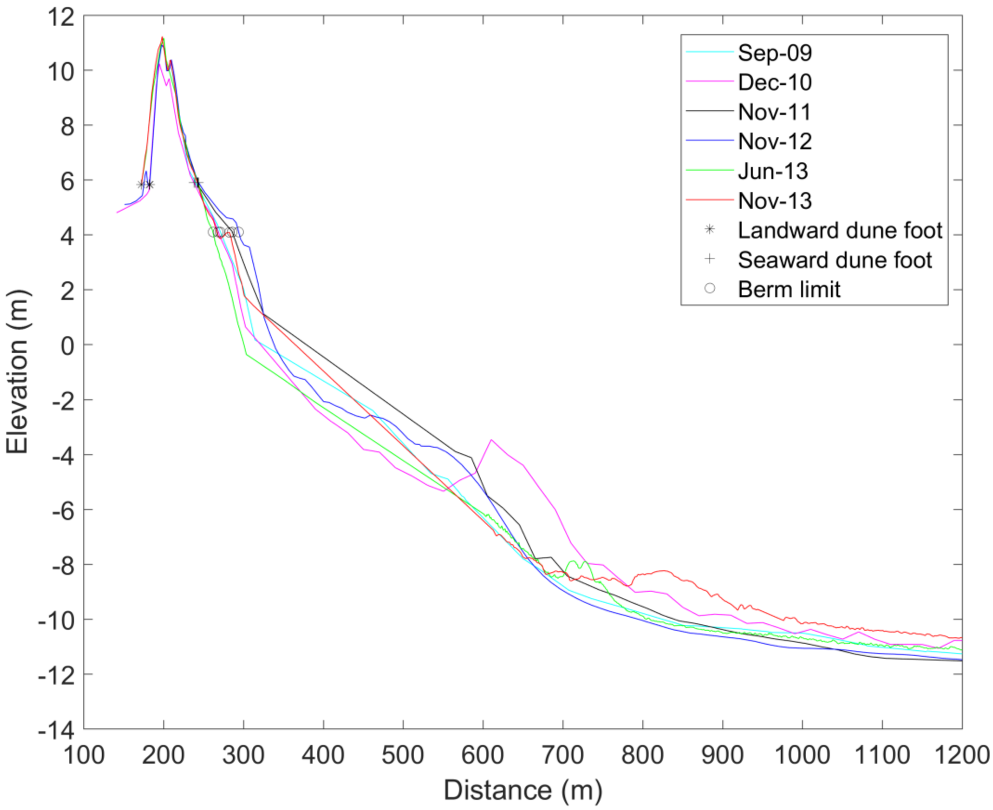


Figure 5.7. Topo-bathymetric surveys of profile, between 2009 and 2013 (elevation relative to MSL).

A short analysis of the topo-hydrographic surveys identified a positive sediment balance between Sep-09 and Nov-11, contributing to a total accretion of approximately 66 m^3/m.

Between Nov-11 and Jun-13 about 307 m^3/m were eroded from the profile. Between Jun-13 and Nov-13 a significant accretion of about 902 m^3/m was verified mainly due to sand nourishment works performed in this period (see Table 4.1). The analysis is based on the part of the profile that is covered by all surveys. A pronounced submerged sand bar with a crest elevation at 3.5 m below MSL and volume of 266 m^3/m was also observed in 2010.

The shoreline retreat rate in Costa Nova beach is estimated to be 3.7 m/year (EUrosion, 2006). This rate was included in the CS-model as a constant retreat of the berm.

5.3.2. Model set-up and calibration

The initial cross-shore profile was schematized according to the survey of 20-Sep-09. The Aveiro beach profile type differs from the schematized model profile shape, as there is typically no horizontal berm (see Figure 5.7). On the contrary, the berm can exhibit different slopes over time. In the calibration process, the berm width was defined approximately as half of the beach width, so the berm volume could be correctly represented. The model results are then compared with half the measured berm width. The initial morphologic characteristics of the profile are displayed in Table 5.1.

Table 5.1. Morphological parameters, initial values of variables.

y_L (m)	y_S (m)	y_B (m)	s (m)	$s_{máx}$ (m)	D_B (m)	V_B (m^3)	β_L (rad)	β_S (rad)	β_F (rad)
181	240	255	5	5	5.9	100	0.30	0.14	0.07

The model was calibrated with the measured profiles, following a parameter optimization process in order to obtain the best model results that reproduce the observed beach-dune system response. So, based on this procedure, the parameter C_S (coefficient in the dune impact formula) was set at 1×10^{-3}, which is within the interval 1.7×10^{-4}–1.4×10^{-3} presented by Larson *et al.* (2004) when validating the model with large wave tank and field data. Since the berm was defined as half beach width, after an iterative process of value optimization, the friction coefficient, C_f, was set to 0.01, as a way to reduce the front speed of the wave affected by the friction as it propagates towards the dune face. In the absence of wind data, the aeolian sediment transport was calibrated against the observed profile evolution to a constant rate of 4.6×10^{-7} $m^3/s/m$. The adopted values of q_{ws} and C_s parameters corresponded to a balance between the dune growth and wave impact that could represent the observed dune evolution. The Δ coefficient was assumed equal to 0.1, being in the order of values proposed by Larson *et al.* (2016), and the water temperature was set equal to 15°C.

In 2009, no submerged bar was registered (see Figure 5.7). However, an initial bar volume of 100 m^3/m was assumed for calibration of the CS-model. This volume represents not only the bar volume but also all nearshore deposits. The effect of the beach fills was introduced during the simulation considering individual additions of sediment to the bar volume, due to its proximity to the deposition area (see Figure 5.7, survey from 26-Nov-13). The sand added were specified according to the fill volume presented in Table 4.1 and based on the dumping area boundary.

A depth of closure, D_C, equal to 12.4 m was calculated using Hallermeier's (1981) formula. This value is in agreement with D_C-values usually considered for the Aveiro coast, which are between 12-15 m (Coelho, 2005), and within the observed limit of the vertical variation of the profile (see Figure 5.7).

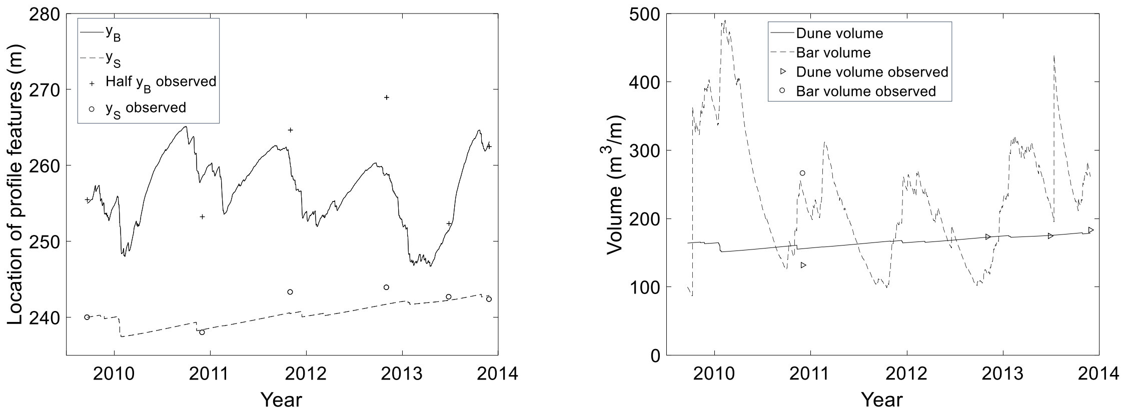
Wave heights were adjusted for oblique wave angles before employed in cross-shore calculations of dune erosion using the formulation by Hanson and Larson (2008),

$$H_0' = H_0\sqrt{\cos\theta} \qquad \text{Eq. 5.11}$$

where H_0' is the modified wave height used in the calculations and θ is the offshore incident wave angle.

5.3.3. Results

In general, the cross-shore model results show good agreement with the observed profile evolution (Figure 5.8a and Figure 5.8b).



a) Result profile: calculated y_S and y_B; observed y_S and y_B

b) Result profile: calculated V_D and V_B; observed V_D and V_B.

Figure 5.8. Comparison between simulated and observed values for seaward dune foot and berm positions and dune and bar volumes.

The bar volume increases during the winter months due to more energetic wave conditions. Significant decreases in dune volume and berm width are observed at the beginning of each winter, when the first storms hit the dune and move large amounts of sediment offshore, feeding the bar. At the end of summer the profile is restored. Sediment has been transported back to the beach from the bar during less energetic wave conditions and wind transport has rebuilt the dunes. These seasonal variations are well represented in the model results.

The major beach nourishment volumes added to the bar volume, V_B, can be identified as instantaneous increases (in Oct-09 and Jul-13). However, the rapid increase that can be observed in 15/26-Jan-10 does not result from fill operations. The beach was subject to frequent wave attack with runup levels exceeding the dune foot, z_D. After this event, the simulated minimum dune volume was observed as well as the highest bar volume (491 m^3/m). The dune foot, y_S, retreated by 2.5 m, and the berm width, y_S-y_B, decreased by 7 m. This extreme event may be the cause of critical damages to the dune structure only registered by the topo-hydrographic survey of Dec-10, evidencing a significant decrease of the dune volume and height in relation to the other surveys.

The simulated seaward dune foot position, y_S, follows the evolution trend of the observed position. The maximum deviations registered between computed and observed values are about 2.8 m and 2.2 m, in Nov-11 and Nov-12, respectively (Figure 5.8a). The berm evolution simulation indicates a slower recovery process compared to the retreat that occurs during storms. The simulated berm width (y_B-y_S) and berm position (y_B) trends follow the observed gains and losses of sediment, with an average deviation from the measured values of about 2.6 m and 3.7 m, respectively. In 2010, 2011 and 2012 the observed berm deviates significantly from the simulated values, reaching a maximum difference of about 10 m in Nov-12. These deviations may result from that the observed berm values were collected at the beginning of winter periods, and that the meteorological effects on the water levels are being neglected. Considering this, the first impacts of the storms might have induced additional dune erosion, increasing the sand transport to the berm, and further increasing the beach width.

The simulated dune volume shows an increasing trend with time (Figure 5.8b) which is in line with observations. However, dune erosion due to the storm in Oct/Nov-10 is underestimated in the model as the observed dune volume is 24 m^3/m lower than the simulated, resulting in the maximum deviation registered during the simulation period. As previously mentioned, the meteorological effects not considered in the SWL data may be inducing this behavior. As discussed before, the topo-hydrographic survey carried out in Dec-10 confirms that critical damages to the dune structure happened before. The average deviation between simulated and measured values of V_D is 8 m^3/m.

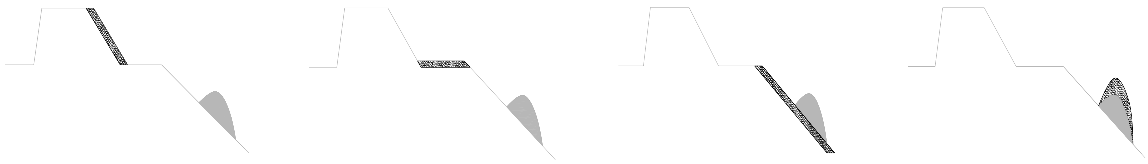
The topographic surveys only show the presence of a bar after the storm in Oct/Nov-10. The model results indicate that the profile surveys are performed at times when the bar volume is close to its minimum value. In Dec-10, the simulated bar volume was approximately 27 m^3/m lower than the observed (Figure 5.8b). At the same time, the model overestimated the observed dune volume suggesting that the impact of the storm is not accurately reproduced by the model. The profiles that show higher retreat rates (Nov-13, Dec-10, and Sep-09) are the same in the model results and in the topo-hydrographic surveys.

5.4. Sensitivity analysis to model performance

In the present section, a sensitivity testing to the model described previously is performed, and example applications are made to evaluate the behavior of different beach fill cross-sections in adjustment to natural wave conditions. Key morphological parameters defining the input beach profile are handled in order to simulate the response of distinct nourished schematized beach profiles in relation to an unnourished situation. Different scenarios were specified as an attempt to assess the impact of changing location, volume, and frequency of placing sand on an open beach by investigating the redistribution of the fill material in the two-dimensional vertical plane.

5.4.1. Methodology

The potential evolution of hypothetical sand nourishment interventions on an open sandy beach was investigated through numerical simulations of distinct design fill schemes using the CS-model. All the simulations were based on the same reference profile (unnourished profile) and subjected to the same wave conditions until a new equilibrium state (implying a complete cross-shore redistribution of the fill material) could be achieved. The first simulations focused on the optimal location for placing sediment, specifying four key cross-shore locations for the fill (see Figure 5.9): high up on the subaerial portion of the beach (on the seaward dune face); along the berm; along the profile (between the shoreline and the depth of closure); and at the bar system. The nourished reference volume considered in the simulations was 0.1 Mm^3 applied over 2 km alongshore, yielding to a cross-sectional volume of 50 m^3/m.



a) Dune b) Berm c) Profile d) Bar

Figure 5.9. Different types of nourishment schemes investigated (varying the placement location).

Subsequently, the bar nourishment scheme was selected and six other hypothetical nourishment scenarios were simulated to focus on the frequency and the magnitude of the intervention. From these six hypothetical schemes, three were set by varying the fill placement schedule: first adding the total fill volume to the bar at the beginning of the simulation period (hereafter referred as concentrated fill or mega-nourishment approach) and then dividing equally the total fill volume in two or four distinct occasions during the simulation period (t=0; t=0 and t=6112; t=0, t=3058; t=6112 and t=9174 time steps). For the last three study cases, different sectional fill volumes (0.1Mm^3 – reference volume, 0.2 Mm^3, 0.5 Mm^3 and 1 Mm^3) were tested following a mega-nourishment approach. All these sectional volumes were also applied for an alongshore extent of the nourishment of about 2 km.

The CS-model was not designed to handle different sediment grain sizes and thus, the fill material was assumed similar to the native sand. Realistic waves and water levels inputs derived from the case study presented in Section 5.3 were selected and used for the simulations. As it was done in Section 5.3, wave heights were adjusted for oblique wave angles using Eq. 5.11 before employed in cross-shore calculations of dune erosion.

The longshore sediment transport gradient was included in the simulations through a continuous sink term in order to describe a coastal stretch hypothetically affected by shoreline recession. For the dune build-up by wind-blown sand, only a constant transport rate was assumed for the seaward side of the dune, whereas for the shoreward dune face slope no wind-blown transport was considered. The idealized cross-section was set according to the typical beach profile shape, describing a flat berm (implying the berm crest at the same level as the dune foot) and a dune (or barrier) with a trapezoidal shape (which can eventually become triangular if significant dune erosion occur). The time step of the simulation was set to 3 hours according to the frequency of the wave records acquisition. The model results were interpreted and compared by taking into account specific design aspects (*e.g.*, methods, fill types, objectives, performance).

5.4.2. Model set-up

A schematic cross-section, based on the input profile previously used in Section 5.3 to represent the beach-dune system evolution at Aveiro coast, has been taken here as reference situation (unnourished profile) for the following numerical applications (see Table 5.2). The same values of the model parameters specified in the Section 5.3.2 were adopted. The shoreline retreat rate (3.7 m/year) recorded at Aveiro coast and previously taken into account was also included in the simulations through a constant of the y_B parameter.

Distinct cross-shore locations for the fill material were set up in the model as follows. Dune nourishment was simulated by imposing an advance of the seaward dune foot position (y_S). For berm nourishment, a different elevation between the crest berm and mean sea level, z_D, (calculated through the ratio between the fill volume and beach width) was considered. In this case, the input model parameters s, y_S, and y_B had to be appropriately adjusted to ensure that the berm crest and the seaward dune foot were set at the same level, as well as applying the same sectional fill volume (see Figure 5.9). The profile nourishment scheme was set through an equivalent seaward advance of the berm position (y_B), determined through the ratio between the sectional fill volume and the vertical distance between the berm crest and the depth of closure, D_c. Finally, the profile nourished at the bar was simulated by adding the total fill volume to the bar volume input parameter, V_B. All nourishment schemes were configured at the beginning of the simulation period (time step: t=0).

Table 5.2. Initial values of variables to characterize the main morphological features of the beach profile for hypothetical nourishment scenarios.

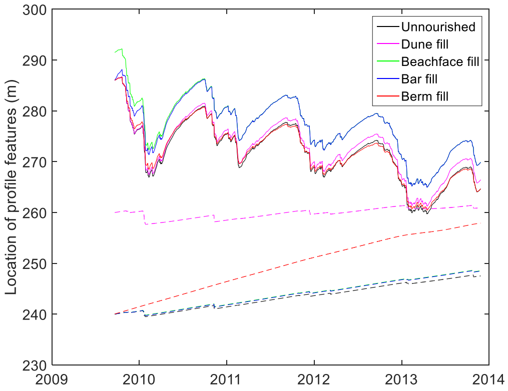
y_L (m)	y_S (m)	y_B (m)	s (m)	$s_{máx}$ (m)	D_B (m)	V_B (m^3)	β_L (rad)	β_S (rad)	β_F (rad)
181	240	286	5	5	5.9	100	0.30	0.14	0.07

5.4.3. Results of simulated scenarios

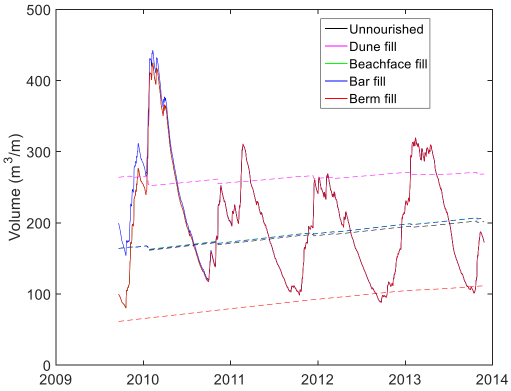
5.4.3.1. Cross-shore location

The purpose of changing the cross-shore location of the fill placement was to analyze how this can affect the nourished profile response, evaluating its temporal and spatial evolution towards an equilibrium state. As the CS-model assumes that no material is lost offshore, the nourished profile response (or its time adjustment) was distinguished here by the time the same cross-sectional fill volume takes to become part of the beach system when subjected to the same forcing conditions.

Figure 5.10 shows the evolution of the seaward dune foot (y_S), berm position (y_B), and the dune and bar volume for profiles nourished with the same amount of sand at the dune, berm, along the profile, and at the offshore bar. In order to be able to compare the results obtained for each scheme, the displacement imposed to the berm and to the seaward dune foot position ($\Delta y_S = \Delta y_B$), for simulating the berm nourishment, was added to the calculated values of y_S and y_B (Figure 5.10a). Due to the berm elevation resulting from the nourishment, a reduction of the dune height, and consequently of the dune volume, had to be imposed to simulate this scheme, so the same profile volume could be considered in the simulations (Figure 5.10b).



a) Modeled results for y_S and y_B.



b) Modeled results for V_D and V_B.

Figure 5.10. Simulation results varying the placement of the nourishment. The continuous and dashed lines represent the modeled berm and seaward dune foot positions in a) and the dune and bar volume in b), respectively.

Overall, results of the cross-shore exchange of the nourished material demonstrated that most of the nourishment schemes differed mainly concerning the time evolution of profile adjustment, whereas the equilibrium states themselves were similar. The same morphological conditions were observed for the bar and profile nourishment schemes after the first winter, suggesting that a quicker fill redistribution takes place when the profile is nourished at the bar: y_B and V_B tend to the same values. The same V_B evolution trend is observed for all designed fill schemes, since its computation is taken to be proportional to the deviation from its equilibrium volume. This explains the gradual decay of the offshore bar volume observed for the bar scheme during its early development, describing the bar volume adjustment towards normal conditions.

For cases when the material is placed high up in the profile (at the dune) it was observed that the fill material takes longer to be redistributed across shore. However, a shift in the forcing conditions towards a more frequent recurrence of storm events, in the early of 2010, forced sediments to move seaward, causing a significant landward movement of the dune foot position, y_S. Since the dune is mostly exposed to waves during storms, the distribution of the nourished sand remains restricted to the occurrence of high-energy conditions, inducing offshore sediment transport to the berm. Although in the dune nourishment scenario the profile adjustment is slower, a trend to achieve the same conditions as for the profiles nourished at active profile and at bar (same values of y_S, y_B and V_D) can be observed in Figure 5.10a. At equilibrium, the same beach width is observed for the three nourishments schemes (dune, beach slope, bar).

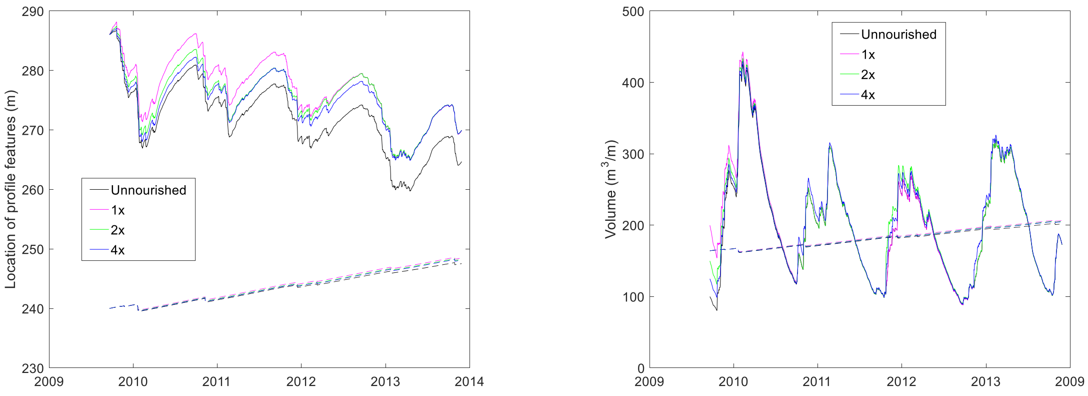
With respect to the berm nourishment, model results showed that an increase in the berm level provides improved dune protection against storms, reducing the probability of the waves attacking high up in the profile. During recovery periods, as dune erosion occurs with less frequency (preventing sediments from being transported from the dune to the berm), the profile that was not nourished presents a more seaward advanced berm position. Still, the profile nourished at the berm and the unnourished profile showed similar values for the berm position, y_B, since the change in the shoreline position is inversely proportional to the berm height.

The simulated seaward dune foot position shows an increasing trend with time for all nourishment schemes due to the wind-blown sand transport (moving sediments from the berm to the dune). However, for the berm fill, a quicker build-up of the dune is observed as a result of the lower wave impact over the dune, implying a relatively stronger contribution from the wind.

Since no offshore losses are being taken into account in the simulations, the model results obtained for the unnourished profile can be described by a general profile translation in relation to the equilibrium states achieved for the nourished profiles. Apart from this being a quite logical response to the nourishment activity, several authors (Park *et al.*, 2009; Marinho *et al.*, 2017a) have found a more active sediment exchange between the nearshore and offshore areas than expected. Also, Marinho *et al.* (2017a), when analyzing the short-term responses of underwater fills through their spatial and temporal variations, detected some offshore-directed losses in which sediments were driven to deeper waters (acting as a sink for the sediments).

5.4.3.2. Schedule for fill placement

The impact of changing the chronology for placing the same cross-sectional fill volume is evaluated here. Figure 5.11 displays the model results for the seaward dune foot (y_S), berm position (y_B), and dune and bar volume variation for a profile with different timing of the fill placement.



a) Modeled results for y_S and y_B.

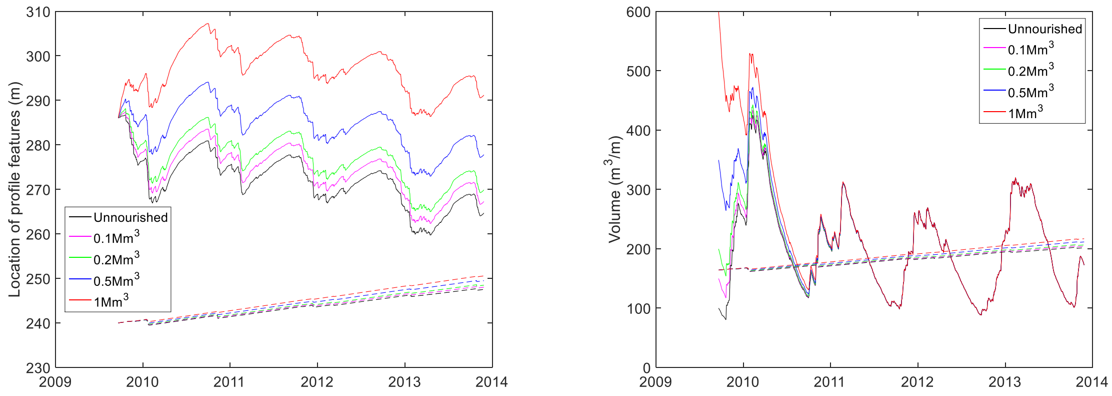
b) Modeled results for V_D and V_B.

Figure 5.11. Simulation results varying the fill placement schedule. The continuous and dashed lines represent the modeled berm and seaward dune foot positions in a) and the dune and bar volume in b), respectively.

Overall, the simulation results showed that a concentrated fill placement in time provides a rapid advance of the shoreline position (y_B), although all the different schemes for fill placement tend to reach the same values of y_B after the total fill material has been placed at the bar. The concentrated fill reduces the impact force from the waves hitting the dune face since waves propagate a larger distance to reach the dune foot. Consequently, the eroded dune mass (quantity of sand transported from the dune to the berm) to balance the build-up by wind processes is lower, contributing to a pronounced dune growth. The same reason explains why the seaward dune foot ends up at a more retreated position when the fill placement is split up in different occasions. Furthermore, integrating the beach width in time, the concentrated fill presents a larger accumulated beach width at the end of the simulation, providing longer coastal protection. In terms of shoreline position, y_B, the more advanced position was obtained for the profile nourished at four occasions, whereas the beach width is narrower when a mega nourishment is employed (at t=0).

5.4.3.3. Sectional volume

What was desired here was to evaluate the performance of the model by simulating different sectional fill volumes (0.1 Mm^3/m, 0.2 Mm^3/m, 0.5 Mm^3/m, and 1 Mm^3/m). Figure 5.12 displays the evolution of the seaward dune foot (y_S), berm position (y_B), and dune and bar volumes for a profile nourished with increasing sectional fill volumes.



a) Modeled results for y_S and y_B.   b) Modeled results for V_D and V_B.

Figure 5.12. Simulation results varying the sectional fill volume. The continuous and dashed lines represent the modeled berm and seaward dune foot positions in a) and the bar and dune volume in b), respectively.

In agreement with the model results obtained in 5.4.3.1 and 5.4.3.2, an increase in the fill volume resulted in an increase of the beach width (the bar goes back to its equilibrium shape, gradually releasing sediment towards the beach – see Figure 5.12). The model includes a physically based approach to simulate the cross-shore sediment transport over decades, so, the larger the fill volume dumped at the bar, the longer the time will be required to redistribute the nourished material (note in Figure 5.12 that the time adjustment of V_B increases with the nourished volume). Although the time to reach a new equilibrium state depends on the sectional volume applied, it was verified that the profile usually takes one seasonal cycle to redistribute the nourished sand (storms events accelerate the distribution of the fill material). Also, as offshore losses are not included, the values of y_S and y_B are proportional to the increase in the fill volume (see Figure 5.12). However, due to the frictional losses over the berm, a widening of the berm implies a decrease in the wave impact force hitting the dune, meaning that after a certain sectional fill volume, the increase of fill material does not have any additional benefit on the profile. This yields an increased ability for the wind to build up the dune, which considering the sand availability will imply a general decrease of the beach width with time (wind blows sand towards the dune, increasing y_S and retreating y_B), consequently intensifying again the wave impact force hitting the dune. The maximum benefit from nourishment was shown to depend on the beach width necessary to dissipate all the incoming wave energy.

5.5. CS-model: additional settings

The CS-model integrates only one module for computing the subaqueous CS material exchange, designated as berm-bar material exchange. The first version of this module, firstly presented by Larson *et al.* (2013) and briefly described in Section 5.2.3 builds upon the one-bar theory, where the evolution of one single bar is coupled to the berm region (or shoreline). In **Paper IV** (Marinho *et al.*, 2017c), efforts have focused on improving this module to better account for beach systems consisting of two bars (inner and outer, Section 5.5.1) as well as the feeder response over time of nearshore dredger material bars, intended to function as beach nourishment (Section 5.5.2).

5.5.1. Theory for two-bar system

Many wave dominated sandy coastal systems across the world are characterized by the presence of one or more subtidal longshore bars (Larson and Kraus, 1992; Ruessink and Kroon, 1994; Różyński and Lin, 2015; Ruggiero *et al.*, 2016; Bouvier *et al.*, 2017; Walstra and Ruessink, 2017; Aleman *et al.*, 2017; Stwart *et al.*, 2017). For such systems, models are required for simulating the bar-berm material exchange to reproduce: 1) the seasonal behavior of the beach profile; 2) the effects of the sediment release during storms from the dune and the beach to the subaqueous portion of the profile; and 3) the recovery process of the berm during periods of low-energy, when bars tend to lose volume and migrate onshore (eventually welding to the shore).

Reports with focus on the response of multiple bar systems have been disseminated, *e.g.*, Lippmann *et al.* (1993), Ruessink and Kroon (1994), Grunnet and Hoekstra (2004), Pruszak *et al.* (2008), Kroon *et al.* (2008), Różyński and Lin (2015), Aleman *et al.* (2017). At multi-sand bar sites, waves may repeatedly break and reform as they propagate towards the shore. Consequently, the behavior and alongshore variability of inner bars and the shoreline position is often influenced by wave breaking patterns on the outer bars. Several theories have been advanced to explain the formation of longshore bars. Almar *et al.* (2010), for instance, concluded that the outer bar was most influenced by the offshore waves while the inner bar dynamics were most influenced by the tide range. When the outer bar undergoes a net offshore migration and degenerates, some authors report that the shoreline and inner bar are more exposed to wave energy and vulnerable to subsequent storm erosion (Price and Ruessink, 2011; Splinter *et al.*, 2016). Ruessink and Terwindt (2000) presented a conceptual model to describe the cyclic behavior of offshore migrating bars. Following this model, a bar goes through three main stages: it is generated close to the shore (in the inner nearshore; stage 1), it migrates seaward through the surf zone (stage 2), and eventually decays at the outer margin of the nearshore (stage 3). Although important insights into the governing processes of interaction between the seabed and the wave forcing have been achieved by several authors regarding the behavior of longshore bars, the actual sediment transport mechanisms determining the bar evolution are still poorly understood by researchers to be parameterized in detail. According to Ruessink and Kroon (1994), bar parameters (such as volume, height, and mean water depth over the bar crest) can be well-linked to the bar stage. Correlations between bar and wave properties have also been discussed by Larson and Kraus (1992).

Aiming to improve the one-bar model performance previously presented in Section 5.2.3, a system consisting of two bars, namely an inner and an outer bar, was studied. A simple wave criterion is proposed for predicting the onshore and offshore movement of the inner and outer bar with reference to their equilibrium condition.

Overall, when waves are small, only an inner bar forms. However, during high-energy wave conditions (*e.g.,* storms), large waves will break offshore and form an outer bar as well. These large waves will reform in the trough and eventually shoal and break again closer to the shore, also helping to maintain the inner bar. Dissipation of energy decreases in the reformed waves, implying a corresponding decrease in the transport rate. Thus, for a multi-bar model, a method or criterion is needed to define how many bars will form for certain wave conditions and sediment characteristics. In the present study, since the focus is on a two-bar system, a simple approach is desirable and a criterion based on the wave characteristics is employed. If the incoming wave height is greater than a certain wave height (hereafter referred as the critical wave height, H_c) then two bars will develop, otherwise, when $H_0<H_c$, the system strives towards only one bar.

The bar volume, as in the one-bar system, is taken as indicator of the transport direction, where a growth in the outer bar volume is associated with a net seaward movement of sand and a decay in the outer bar volume is caused by onshore sediment movement (inducing degeneration of the outer bar). This assumption does not necessarily preclude the model from being able to capture inter-annual cycles and trends in sandbars, as well as shorter (storm) scale response. The inter-annual cyclic bar behavior is included *per se* since the bars in the two-bar model responds to the wave forcing at the input time scale.

The build-up of the outer bar is then taken as an intermittent process confined to the occurrence of high-energy periods.

It was earlier demonstrated by Larson *et al.* (2013; 2016) that the empirical equation for the equilibrium bar volume could be employed to calculate the total sediment volume stored in the inner and outer bar at Duck, USA. Thus, this equation will be used for a multi-bar system to obtain the sum of the inner and outer bar volumes at equilibrium state. The normalized equilibrium bar volume is then given by,

$$\frac{V_{BE}^{TOT}}{L_0^2}=\frac{V_{BE}^{I}}{L_0^2}+\frac{V_{BE}^{O}}{L_0^2} \qquad \text{Eq. 5.12}$$

where the superscript TOT, I and O denote total, inner, and outer equilibrium bar volume, respectively. The question arises on how to partition V_{BE}^{TOT} between V_{BE}^{I} and V_{BE}^{O}. Defining the ratio $\delta = V_{BE}^{O}/V_{BE}^{I}$, then:

$$V_{BE}^{I}=\frac{1}{1+\delta}V_{BE}^{TOT} \qquad \text{Eq. 5.13}$$

$$V_{BE}^{O}=\frac{\delta}{1+\delta}V_{BE}^{TOT} \qquad \text{Eq. 5.14}$$

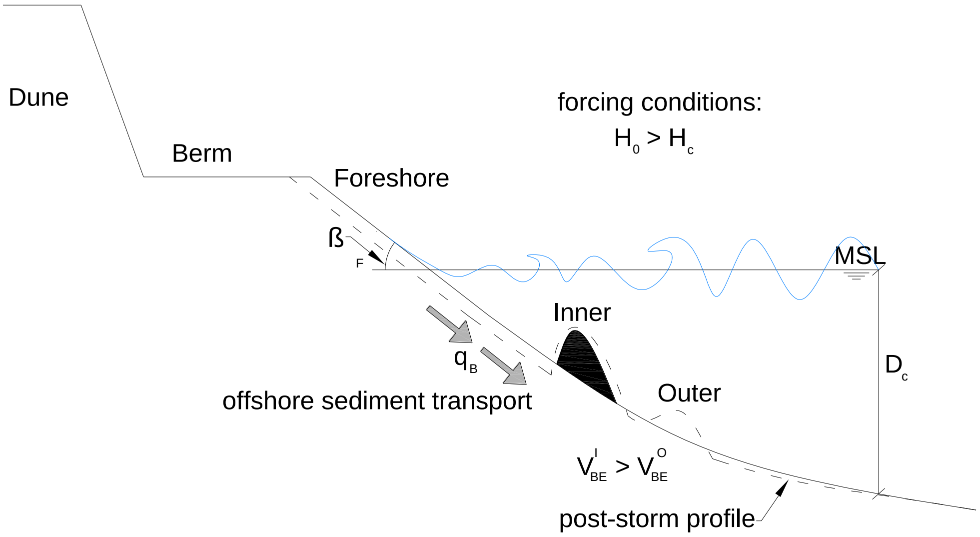
These equations yield how much of the total bar volume belongs to the inner and outer bar, respectively. If δ can be predicted, by using Eq. 5.13 and Eq. 5.14, V_{BE}^{I} and V_{BE}^{O} can be determined. At a first order approach, δ should depend on the relationship between H_0 and H_c; that is, a larger wave height with respect to the critical wave height (H_c) will produce a relatively larger offshore equilibrium bar volume. Based on this observation, the following empirical relationship is proposed:

If $H_0<H_c$, then $\qquad \delta=0 \qquad$ Eq. 5.15

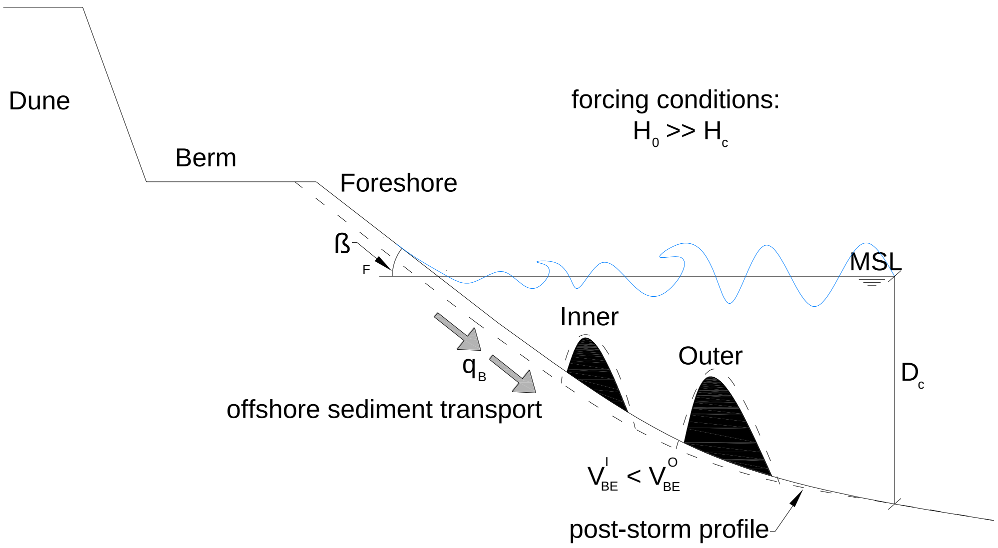
Otherwise, for $H_0>H_c$ $\qquad \delta=\delta_0\left(\frac{H_0}{H_c}-1\right) \qquad$ Eq. 5.16

where δ_0 is an empirical coefficient to be calibrated against data (=1 as a first estimate). The subaqueous processes that build the two-bar system are represented in Figure 5.13. If $H_0<H_c$, then the outer bar will not form or will tend to disappear (V_{BE}^{O}=0 m^3/m), whereas

$H_0 >> H_c$; means that the outer bar will grow relatively larger in relation to the inner bar ($V_{BE}^{O} >> V_{BE}^{I}$).



a) For 0<δ<1, the outer bar starts to form and grow.



b) For δ>1, the outer bar grows relatively larger than the inner bar.

Figure 5.13. Scheme for the evolution processes for a two-bar system.

For each wave condition (at a specific time step), Eq. 5.13 and Eq. 5.14 together with Eq. 5.15 and Eq. 5.16 are solved numerically. The change in the inner and outer bar volume are computed in the same manner as before for the one-bar system, using the analytical solution described in Eq. 5.9,

$$\Delta V^{I}_{B,i}=\left(V^{I}_{BE,i}-V^{I}_{B,i}\right)\left(1-e^{-\lambda^{I}_{i}\Delta t}\right) \qquad \text{Eq. 5.17}$$

$$\Delta V^{O}_{B,i}=\left(V^{O}_{BE,i}-V^{O}_{B,i}\right)\left(1-e^{-\lambda^{O}_{i}\Delta t}\right) \qquad \text{Eq. 5.18}$$

where subscript i denotes a certain time step. The new volume at time step i+1 is obtained from $V^{I}_{B,i+1}=V^{I}_{B,i}+\Delta V^{I}_{B,i}$ (for the inner bar) and $V^{O}_{B,i+1}=V^{O}_{B,i}+\Delta V^{O}_{B,i}$ (for the outer bar). The λ coefficient, in Eq. 5.17 and Eq. 5.18, will depend on whether the inner or outer bar grows or decays. However, as the inner and outer bars are located at different water depths, different behavior should be expected.

According to Larson and Kraus (1992), once the outer bar is formed, it will only be exposed to wave breaking and large sand transport during severe storms, with the transport induced by non-breaking waves producing slower changes in the bar shape. On the other hand, the inner bar experiences wave breaking during most of the year, resulting in relatively faster response compared to the outer bar ($\lambda^{O}_{0}< \lambda^{I}_{0}$). Also, when onshore sediment transport and bar volume reduction occurs, a different multiplier ($\lambda^{on}_{0}=C_c\lambda_0$) to reduce the coefficient λ_0 should be adopted for the inner and the outer bar: $C^{I}_{c}>C^{O}_{c}$ (the values of these coefficients should be determined through calibration against data).

As an exchange of material continually takes place within the surf zone, depending on changes in the nearshore wave conditions, it might be necessary to include an exchange between the inner and the outer bar volumes in the calculations.

In cases when no exchange of material is admitted between the inner and outer bar, the total bar volume going into or from the subaqueous portion of the profile is defined by:

$$q_B(t)=\Delta V^{TOT}_{B}/\,\Delta T,\ \text{where}\ \Delta V^{TOT}_{B}=\Delta V^{I}_{B}+\Delta V^{O}_{B} \qquad \text{Eq. 5.19}$$

The offshore or onshore sediment transport volume (from the berm to the bars or vice-versa) is given by the sum of the total variation for both bars (inner and outer).

For cases where exchange of material between the bars is admitted, the outer bar volume variation is computed first (ΔV^{O}_{B}) and then the following conditions are checked:

1) If $V^{O}_{BE,i} < V^{O}_{B,i}$ (or $\Delta V^{O}_{B}<0$) there is onshore sediment transport, implying that the outer bar is releasing sediment towards the beach. In this case, the sediment will

be transported to the inner bar. So, before computing the inner bar volume change based on its equilibrium value, the inner bar volume must be updated with the volume that comes from the outer, ΔV_B^O. In this situation, the total bar volume that will be transported to the berm will be given by the inner bar volume change (ΔV_B^I):

$$q_B(t)=\Delta V_B^I / \Delta T \tag{Eq. 5.20}$$

2) If $V_{BE,i}^O > V_{B,i}^O$, there is offshore sediment transport and the outer bar is growing. In this case, before computing the inner bar change it is determined whether the inner bar volume has enough sediment to provide to the outer bar, *i.e.*, if $V_{B,i}^I >$ $\Delta V_{B,i}^O$. If this condition is not met, the inner bar volume will disappear totally ($V_{B,i}^I$=0) and the remaining sediment needed to fill the outer bar will be transported from the berm.
3) If $V_{BE,i}^O > V_{B,i}^O$ and $V_{B,i}^I > \Delta V_{B,i}^O$ then the inner bar will provide the sediment needed to the outer bar. In this situation, the same procedure as in the case where there is onshore sediment transport is adopted, computing the sediment transport rate between the berm-bar regions as a function of the inner bar change.

In Chapter 6, the two-bar evolution model just described is validated towards high-quality data collected at Duck, North Carolina, USA, which is a typical site where two longshore bars usually form in the nearshore.

5.5.2. Hypothetical bar equation for nearshore placements

Recycling appropriate dredged material resulting from inlet maintenance dredging operations and/or deepening activities of harbors is typically employed as a sustainable alternative to bypassing of sediment and maintaining beaches (Smith *et al.*, 2017; Marinho *et al.*, 2017a). In this context, for practical and economic reasons, placement of dredge sediment in the subaqueous portion of a downdrift beach becomes more attractive than in the subaerial zone, since dual underwater operations may be realized at considerably less time and cost, minimizing the effort required for positioning of the sediment (Gravens *et al.*, 2003). Also, the material placed in the nearshore need not to be exactly compatible with the beach sediments, because sorting induced by waves and currents will tend to drive finer sand offshore and coarser sand onshore (Larson and Hanson, 2015).

In the previous sections, a model based on empirical relationships was described as an attempt to simulate the evolution of individual longshore bars (or, representative morphological volumes), as well as the cross-shore exchange of material between the berm and the bar region. However, through the study of the response of natural longshore bars with respect to the incoming waves, it is possible to derive criteria that could be applicable for predicting the cross-shore evolution of mounds placed nearshore. In this light, the outer bar is of particular interest because it is typically located in water depths where common dredging equipment can have access, allowing the placement of dredged material in the nearshore. Here, a simple approach is proposed to obtain a preliminary prediction of the migration rate of constructed sand mounds by numerically solving a hypothetical bar equation. In this study, the development of a criterion for predicting the evolution of nearshore mounds was based on the response of hypothetical outer bars subjected to transport by non-breaking and breaking conditions, that is, mounds placed within the surf zone, where the cross-shore morphological development can be dominated either by non-breaking or breaking waves.

As demonstrated earlier, with the theory developed for systems characterized by the presence of two bars, different volumes can be modelled for the inner and outer bar. However, it was also shown that Eq. 5.12 can be employed when just one bar forms, where $V_{BE}^{TOT}=V_{BE}^{I}$ and $V_{BE}^{O}=0$. In such situations, the outer bar will attain an equilibrium bar volume equal to zero which, once nourished artificially with a certain volume (V_{B}^{O}), will gradually decay towards the equilibrium state described by $V_{B}^{O}=0$ m^3/m. Simultaneously, due to the bar-berm coupling system, a continuous widening of the beach (or shoreline advance) is expected to occur. Based on that, Eq. 5.18 can be rewritten:

$$\Delta V_{B,i}^{O}=-V_{B,i}^{O}(1-e^{-\lambda_i^{O}\Delta t}) \qquad \text{Eq. 5.21}$$

According to Eq. 5.21 with $V_{BE}^{O}=0$ m^3/m the condition $0<V_{B}^{O}$ will be always fulfilled, leading to an uninterrupted onshore-directed sand movement. According to Smith *et al.* (2017), the onshore migration of sand and beach recovery is a gradual process and only prevails during periods of low wave steepness. At the same time, it is considered that the offshore mounds may be exposed to a wide range of wave conditions, including wave breaking. However, the tendency for material to be transported onshore is much greater under the action of non-breaking waves in comparison with breaking waves (Larson and Kraus, 1992).

Another important factor to take into account when reproducing the evolution of a feeder mound is the depth of placement because the morphological responses occurring along the sloping sea bottom are expected to be different as a result of changing sediment transport rates (Ruessink and Terwindt, 2000). If sand is placed at the top or seaward of the breaker bar or even in a more offshore position, a different impact or at least a different time adjustment towards equilibrium should be expected (Bodge, 1994). Thus, a rational criterion or method is desirable to determine the overall response of the artificial mound for the incoming waves. Through the study of the response of natural longshore bars, in particular the response of outer bars, Larson and Kraus (1992) have proposed a procedure for predicting the cross-shore movement direction (onshore/offshore) of material placed in the nearshore zone intended to function as beach nourishment. These authors investigated different combinations of dimensionless parameters, such as, wave steepness, dimensionless fall speed and wave height over grain size diameter to develop a criterion that could distinguish accretionary and erosional events. Here, bar degeneration by depth-limited breaking waves is investigated through a simple approach based on wave height.

If $H_0<H_1$, then (calm wave conditions; non-breaking waves):

$$\Delta V_B^O=-V_{B,i}^O(1-e^{-\lambda_1^O \Delta t}) \text{ , } \lambda_1^O=C_C^O\lambda_0 \qquad \text{Eq. 5.22}$$

Else $H_0>H_1$ (breaking conditions):

$$\Delta V_B^O=0 \qquad \text{Eq. 5.23}$$

where H_1 represents the wave height limit for the groups of waves that will break at depths where the outer bar is located. With the assumption that breaking waves are the main cause for seaward sediment transport (or a limiting factor on the depth to the bar crest, h_c), the minimum depth over the bar should be of the same magnitude as the breaking wave height, H_b. Numerous formulas have been proposed to relate the breaking wave height to the water depth. Larson and Kraus (1989) found a relationship between the depth to bar crest (h_c) and the breaking wave height (H_b) based on analysis of profile change in LWT experiments:

$$h_c=0.66H_b \qquad \text{Eq. 5.24}$$

An example of how the profile may change the evolution of a nearshore sand mound for certain wave conditions is hypothesized. If the waves are small ($H_0<H_1$), it is assumed that non-breaking waves will act across the bar and the incident waves will break closer to the shore, promoting onshore sediment transport of the dumped material. During energetic conditions described by $H_0>H_1$, wave breaking prevails and the sediment transport will be considered to be offshore-directed, producing no variation in the offshore mound volume, $\Delta V_B^O=0$. Thus, during smaller waves the nearshore mound is intended to be "active" and designed to release sediments towards onshore, promoting accretion on the beach, whereas for wave heights larger than the breaking wave height, the nearshore mound is regarded to be stationary. As a way to take into account the typical cross-shore transport process on the nearshore mound, inducing dispersion or deflation in relief during non-breaking conditions, it is possible to assume that the material released from the mound go through the surf zone before ends on the berm, admitting in this way transport of the fill material to the inner bar (representative of the inshore portion of the profile).

In the following chapter, field data sets collected at Silver Strand, California, and Cocoa Beach, Florida (USA), in connection with field experiments involving nearshore placement of dredged material, are employed for model calibration and validation.

5.6. Summary

A numerical model with a simplified long-term description of the beach profile evolution, accounting for dune erosion and recovery, overwash/breaching, and the exchange of material between the bar and the berm (CS-model; Larson *et al.*, 2016) has been herein enhanced and applied for a case study and then for a sensitivity test in the context of hypothetical nourishment interventions undertaken on an open sandy beach.

The results of the implementation of the CS-model at a study site (Barra-Vagueira coastal stretch) evidenced their high potential to contribute to improve coastal planning and management, as they could properly reproduce the evolution of the beach-dune system during the measured period 2009-2013, proving to be a valuable tool for adaptation and anticipation of the future coastal needs. This application has served also to calibrate the model for a sensitivity testing encompassing multiple hypothetical nourishment interventions undertaken on an open sandy beach. Overall, the CS-model has driven to useful simulations detailing the evolution of distinct fill design schemes and determining the time scale and movement of the fill material. Regarding the cross-shore exchange of nourished material, the analysis demonstrated that most of the nourishment schemes differed mainly concerning the time evolution of profile adjustment towards a new equilibrium state (which is dependent on the fill volume and placement), whereas the equilibrium states themselves were similar. Due to the coupling between the berm and the bar, placement along the profile and at the bar showed similar behavior, quickly reaching the same equilibrium states (typically during one seasonal cycle). On the contrary, simulation of dune nourishment indicated that the material remains high up in the profile, requiring longer periods to adjust compared to the other schemes, being highly dependent on the occurrence of energetic events to redistribute the nourished sand. An increase in the berm height acted as an additional dune protection against storms, since the probability of waves reaching the dune decreases, preventing erosion. It was verified that after a specific nourishment volume, the profile does not benefit from an increased fill volume. The schemes tested with different placement chronology tend to reach similar values for the berm position (y_B) after the same nourishment volume has been placed in the profile. However, integrating the beach width in time, the concentrated fill presented larger accumulated beach width, implying protection during a longer time period.

A major conclusion from this application is that different types of nourishments may serve different purposes. To strengthen the dune system over time, berm nourishment may be an appropriate solution, decreasing the probability of the waves reaching the dune foot and also promoting the build-up of the dune by wind. To protect the area around the shoreline on a short-term basis (*e.g.*, emergency operations due to storm damage is required), nourishment of the profile or at the bar may be suitable to get a faster cross-shore distribution of the fill. Finally, a long-term solution would be dune nourishment, where a storm surge will gradually distribute the fill material along the profile, increasing the berm width until new equilibrium condition prevails.

An extended version of the subaqueous module integrating the main algorithm of the CS-model to calculate bar-berm material exchange has been also developed. Efforts have focused on improving the model to better reproduce the overall shift in material between the subaerial and subaqueous portions of the profile by taking into account the long-term evolution of multi-bar systems and the response of offshore mounds placed in the outer part of the nearshore zone to act as active or feeder bars (for beach nourishment purposes). The model is based on simplifications of the governing processes, where bar volume evolution determines the transport direction, *i.e.*, bar growth implies offshore sediment transport and bar decay corresponds to onshore sediment transport.

As a first attempt, a two-bar model was derived, where both growth and decay of individual bars are computed with respect to a representative subaqueous morphological volume, or total bar volume, defined at equilibrium, but without regard to the details of how the material may be deposited in or removed from the surf zone. The actual sediment transport paths resulting in the bar evolution are complex and contributions from both shoreward and seaward sides are expected. The presented two-bar model, rather than resolve the fine details of the profile response (or bar shape), relies on a simple approach to compute volume changes distributed between the two bars, with the assumption that larger waves result in more material in the bars compared to smaller waves (quantified based on data). A transfer of material from offshore deposits (longshore bars) towards shallower portions was also found to be important to incorporate, once an exchange of material continually takes place between these areas, depending on change in the nearshore wave conditions. As opposed to the deeper bars, which are exposed to wave breaking only during large storms, the surf zone experiences breaking waves during most of the year. Thus, a rapid response rate is expected for this region, *i.e.*, a considerable sensitivity to changes in the nearshore, affecting also the shoreline movement. The present model does not resolve the necessary hydrodynamic quantities to predict cross-shore sediment transport rates in the surf zone (as the SBEACH model does for example). Instead, from a regional perspective, the total volume corresponding to the subaqueous portion of the profiles is described as a function of the bar volume variation computed in relation to its equilibrium value. A representative morphological volume for the inshore area in the model, in order to better simulate the transport of the fill material in the surf zone was incorporated.

In Chapter 6, the developed numerical solutions (presented in Section 5.5.1 and 5.5.2) are calibrated and validated in standalone mode at three field sites from the United States: Duck, North Carolina (NC), where two natural longshore bars (an inner and outer bar) typically form; Silver Strand, California (CA), where a nourishment was placed on top of an existing bar; and Cocoa, Florida (FL), where an artificial offshore bar was located in deep waters.

CHAPTER 6

MODEL VALIDATION AND APPLICATION

Chapter structure

6.1. Duck, North Carolina, USA

- 6.1.1. Background and data employed
- 6.1.2. Model set-up and calibration
- 6.1.3. Results and discussion

6.2. Silver Strand, California, USA

- 6.2.1. Background and data employed
- 6.2.2. Model set-up and calibration
- 6.2.3. Results and discussion

6.3. Cocoa Beach, Florida, USA

- 6.3.1. Background and data employed
- 6.3.2. Model set-up and calibration
- 6.3.3. Results and discussion

6.4. Summary

6. MODEL VALIDATION AND APPLICATION

The present chapter is developed in line with the previous one, aiming at the validation of the developed numerical approach presented in Section 5.5.1 and 5.5.2, which focuses on the subaqueous cross-shore beach profile response for applications in coastal evolution models, describing processes at the decadal scale.

In the previous chapter, efforts were made to expand the theory of the evolution of one single bar to a multi-bar system, where the volume of the individual bars and their response were described. So, firstly in this chapter, the two-bar model is tested with field data from Duck, North Carolina, USA, where two bars (inner and outer) frequently form. The prediction of the outer bar response is seen here of particular interest, because it is located in water depths where, for instance, typically available equipment can access for nearshore placement of dredged material, providing a method for estimating the response of offshore mounds (artificial bars). Also, it is understood that when disturbing the natural conditions (as the example of the offshore mounds), it may be possible to observe strong signs/responses in the beach morphological behavior, offering a mean to investigate the bar behavior in a more fundamental way, as marked perturbations to the system have occurred.

In recognition of the potential attributes of placing material nearshore for serving as a reservoir of sand in promoting beach growth and the dissipation of wave energy, several reports about nearshore disposals have been published, for example, Andrassy (1991), Bodge (1994), Larson *et al.*, (1999), Barnard *et al.* (2007), Larson and Hanson (2015), Smith *et al.* (2017), and Marinho *et al.* (2017a; 2018b). Although material placed in the nearshore becomes a part of the littoral system, benefits to the beach are still difficult to quantify. The developed model is also employed to numerically solve hypothetical bar equations representing offshore mounds as they migrate towards the shore and become a part of the beach face. The model is applied to simulate nearshore sand placements as hypothetical natural bars for cases from Silver Strand, CA, and Cocoa Beach, FL, where in the latter case natural subtidal bars were not found during the surveyed period.

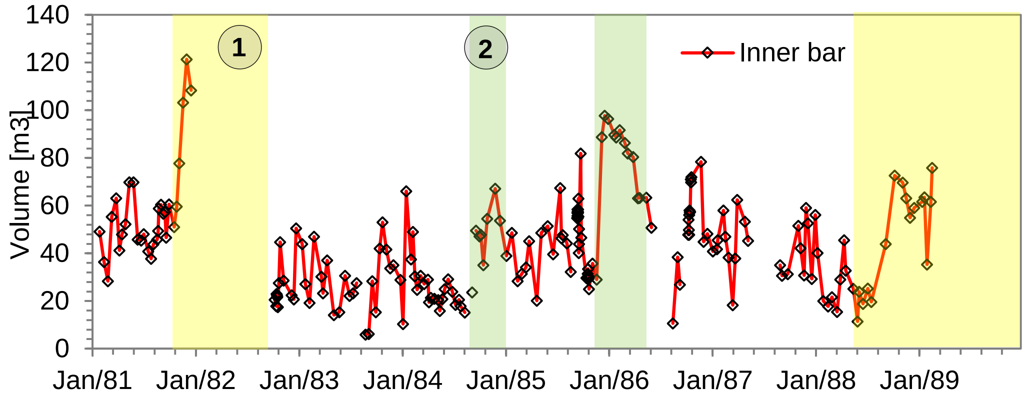
6.1. Duck, North Carolina, USA

6.1.1. Background and data employed

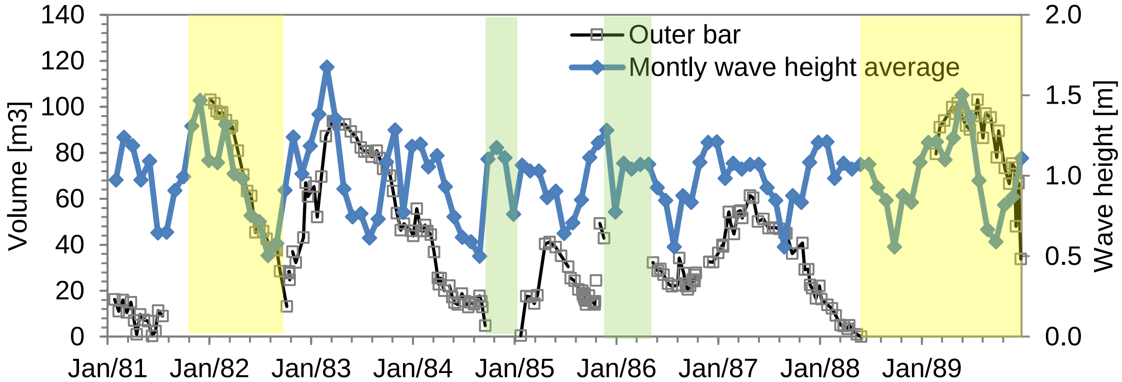
In order to illustrate the properties of the developed model, an example is provided to reproduce the evolution of two longshore bars (inner and outer) that usually appear in the nearshore at Duck, North Carolina, USA. Time series of waves and beach profiles measurements, collected 2-3 times per month by the Field Research Facility (FRF) of the U.S. Army Corps of Engineers, were used to model the volume of individual bars from 26-Jan-81 to 28-Dec-89.

The wave data employed were recorded with a waverider buoy located in 18 m water depth, directly off the FRF research pier. Wave height was obtained as the energy-based significant wave height and wave period was determined as the period corresponding to the peak in the energy spectrum (Larson *et al.*, 2013). The nearshore bathymetry at FRF has been surveyed along four cross-shore lines located far from the disturbing influence of the research pier (Line 58, 62, 188 and 190, see Howd and Birkemeier, 1987). Since the general response of the beach profile to the prevailing waves at the four lines indicated similar long-term behavior, only data from Line 62, which has the most representative response in terms of bar movement and the largest number of surveys available (Larson and Kraus, 1992; 1994), were considered in this study. Beach profile data related to Line 62 have been previously analyzed by Larson and Kraus (1992) to obtain detailed morphological properties of two bar features (inner and outer) with respect to a least-square fitted equilibrium profile to the computed average surveying profiles (including volumes and bar crest location). These data were considered here for model calibration and validation.

Overall, two measurements periods were identified by Larson and Kraus (1992) during which the inner bar consistently moved offshore to become the outer bar. These periods were observed just after the surveys of 28-Sep-81 and 09-Sep-88, where the offshore-moving bar became the outer bar. Although a distinction between the inner and the outer bar is appropriate for modelling purposes, this division is not straightforward. As referred previously, the cyclic behavior of multi-bar systems has been discussed extensively. However, several nearshore morphological phenomena are still not well described. The inter-annual migration pattern of a bar and its relationship to the onset of a new inner bar is still poorly known. Recognizing the rudimentary knowledge for establishing relationships between aggregated short-term processes and phenomenological medium-term bar behavior in a quantitative way, in the two-bar model, the inter-annual cyclic bar behavior is included *per se* (disappearance of the outer bar is implicitly described as the equilibrium bar volume can become zero). The build-up of the outer bar is taken as an intermittent process confined to the occurrence of high-energy periods (H_0>H_c). In the present study, the question remains under which conditions the inner bar, during the migration stage, should be recognized as the outer bar. For that purpose, the location of the bar was regarded as the decisive parameter. Based on the Larson and Kraus (1992) analysis of the FRF data, Figure 6.1 displays the volume and Figure 6.2 the bar crest depth, for the inner and outer bars, along time.



a) Inner bar



b) Outer bar

Figure 6.1.Volumes for inner and outer bar and monthly average of the measured wave height. Yellow shaded areas correspond to periods when the inner bar has migrated seaward to become the outer bar. Green shaded areas represent the periods when the outer bar has become flat, but reappearing after that at the same location. Numbers 1 and 2 highlight the periods of profile surveying that are further down displayed in Figure 6.3 and Figure 6.4, respectively.

Through analysis of the temporal variation in the observed outer bar volumes (see Figure 6.1), four cycles encompassing bar growth and decay can be identified during the measured period (1981-1989): 26-Jan-81 to 17-Jul-81, 07-Oct-82 to 20-Sep-84, 25-Jan-85 to 21-Nov-85 and 16-May-86 to 02-Jun-88. These time periods were based on the first and last survey revealing an identifiable outer bar feature for time series of consecutive surveys with an outer bar present.

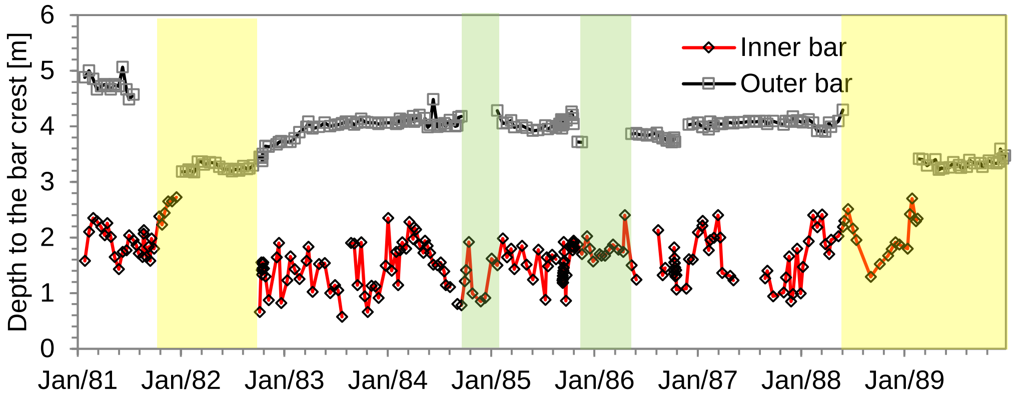


Figure 6.2. Depth of the bar crest for inner and outer bar. Yellow shaded areas correspond to periods when the inner bar has migrated seaward to become the outer bar. Green shaded areas represent the periods where the outer bar has become flat, but reappearing after that at the same location.

As previously mentioned, after the outer bar disappeared, the offshore movement of the inner bar to become the outer bar was observed during two periods: 28-Sep-81 to 07-Oct-82 (see Figure 6.3) and 09-Sep-88 to 28-Dec-89. Duck profile measurements have captured the termination of a bar cycle and the onset of the offshore migration of the inner bar from 28-Sep-81 to 07-Oct-82 and 09-Sep-88 to 28-Dec-89, providing an opportunity to evaluate the trigger point for a new cycle and its relationship to the outer bar response. Figure 6.3 displays times series of surveyed profiles collected between 28-Sep-81 and 07-Oct-82, where the onset of a new bar cycle can be distinguished: the decay process of the outer bar was followed by the onset of the offshore migration of the inner bar, thereby promoting the formation of a new bar near the shoreline.

The surveys indicated that the pronounced migration pattern of the inner bar appearing on the 28-Sep-81 and 09-Sep-88 (see Figure 6.1a), was preceded by a marked growth in the inner bar volume. According to Figure 6.1b, prolonged intermediate conditions (note that H_s presents a short range of variability), encompassing non- or weakly breaking conditions might be the main factor for the decay of the outer bar. The most distinctive part is that the outer bar became flat before the inner bar entered its migration stage. In fact, the inner bar only started to move consistently offshore when storms arrived at the coast, occurring during the autumn and winter season (see Figure 6.4 together with Figure 6.1). It seems that a shift in the forcing conditions was the triggering point for further offshore migration of the inner bar.

During the decay stage of the outer bar, significant fluctuations in inner bar volume and location were observed before the inner bar started to migrate consistently offshore. These fluctuations were attributed to the outer-bar decay condition yielding a more active inner nearshore bar zone. It was confirmed that even the offshore migration process is not a continuous phenomenon, but an intermittent process restricted to high-energy events. Small-scale fluctuations (onshore/offshore shifts of the bar crest) were observed when the inner bar approached the outer nearshore zone, proving that non-breaking conditions (see period of lower waves in Figure 6.4 together with Figure 6.1) have induced minor changes in the bar position.

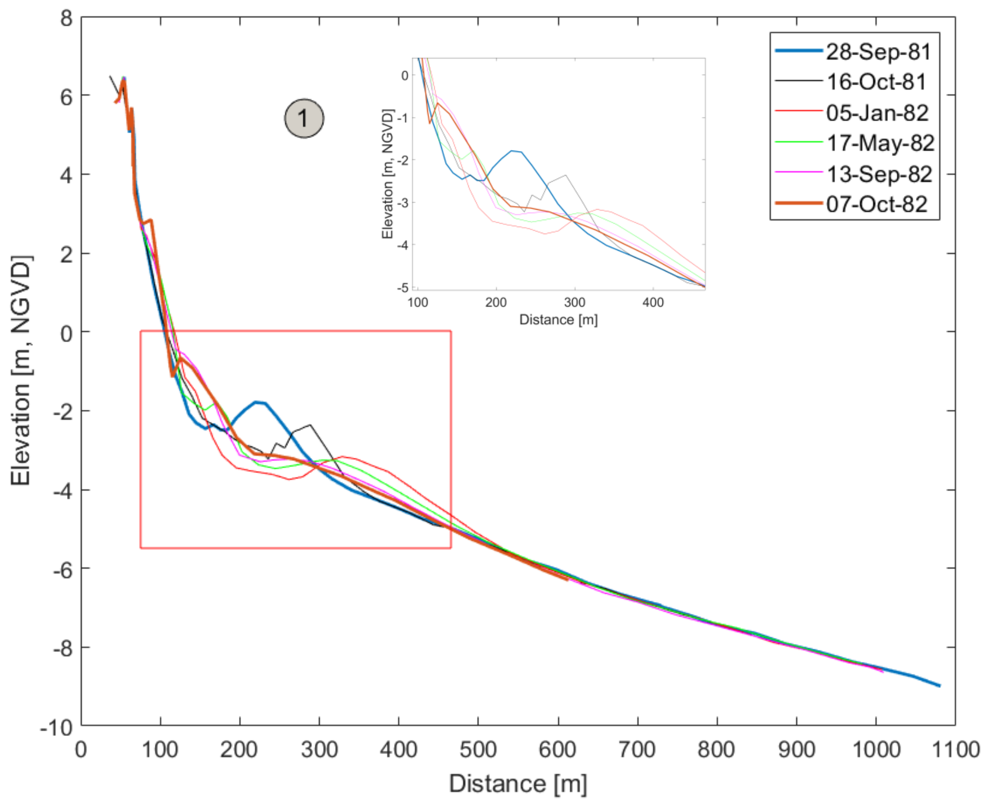


Figure 6.3. Surveyed profiles for Line 62 during the offshore progression of the inner bar to become the outer bar (28-Sep-81 to 07-Oct-82).

The decay and growth of the outer bar was also observed during 20-Sep-84 to 25-Jan-85 and 21-Nov-85 to 16-May-86. However, during these periods, no evidence was detected in the surveys regarding a cross-shore progression of the inner bar towards the outer zone. Instead, the observations indicated that the outer bar has regenerated itself and reformed in deeper water (see Figure 6.4). It is hypothesized that this could be associated with more active sand transport promoted by a more frequent recurrence of breaking conditions, thereby affecting the transport and forcing of the outer bar, which starts growing (see large concurrent wave heights, Figure 6.1).

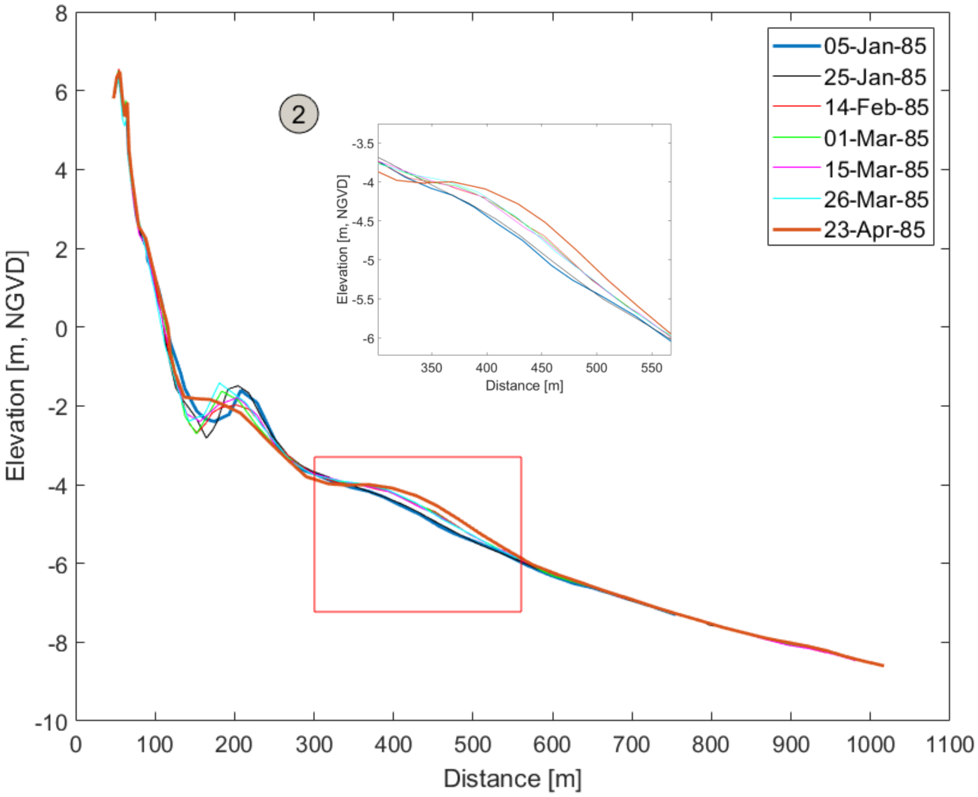


Figure 6.4. Surveyed profiles for Line 62 during the outer bar formation offshore (5-Jan to 23-Apr, 1985).

Comparing with the inner bar observations, Figure 6.2 shows that the fluctuations of the outer bar crest location are significantly smaller and much more regular (depth to bar crest is around 4 m). Thus, it was decided that once a new bar has formed close to shore, and until it reaches the outer zone, the bar is considered to be an inner bar. In accordance with this criterion, bar measurements collected between 5-Jan-82 to 13-Sep-82 and 27-Feb-89 to 28-Dec-89 (periods during which the progressive bar experiences a stage described by small variations in position; see Figure 6.2), were assigned as outer bar observations. However, it has to be kept in mind that these assumptions were just defined for comparing observations with the model results.

6.1.2. Model set-up and calibration

The bar evolution equation Eq. 5.5 was applied to simulate the two-bar system behavior at Duck, where a numerical solution was employed following Eq. 5.10. The model was applied for the time period between 26-Jan-81 and 28-Dec-89, using wave measurements with a six-hour time step (Δt=6 h). The time series of the bar measurements was divided into two main periods, where the first one (extending from 1981-1985) was selected for calibration of the site-specific parameters (d_{50}, m, C_B, λ_0, δ_0, H_c) and the second one (from 1985-1989) was used for model validation. Test calculations demonstrated that employing a smaller coefficient to quantify the bar response rate of the outer bar relative to the inner bar yielded improved agreement between calculated and measured bar volumes. The coefficient values expressing the inner and outer bar responses were assigned to minimize the least-square error (ε) defined as,

$$\varepsilon=\left(\frac{\sum_{i=1}^{N}\left(V_B^{obs}-V_B^{cal}\right)^2}{\sum_{i=1}^{N}\left(V_B^{obs}\right)^2}\right)^{1/2} \qquad \text{Eq. 6.1}$$

where λ_0^I=0.0036 h^{-1} and λ_0^O =0.0023 h^{-1}, respectively (*c.f.* Eq. 5.17 and Eq. 5.18). N represents the number of values for which the bar volume was measured. Based on many observations, including Duck (Figure 6.1), bars tend to form quickly during large storms, whereas during non-breaking conditions, the recovery process occurs slowly, as a result of low transport rates. Also, since the inner bar varied more than the outer bar (see Figure 6.1), exhibiting a considerable sensitivity to changes in the nearshore wave conditions, non-breaking conditions are also expected to produce slower changes in the outer bar shape. Thus, a different multiplier (C_c) to reduce the coefficient λ_0 during onshore sediment transport was introduced in the simulations for both bars. The optimal values of this multiplier were set to C_c^O=0.15 and C_c^I=0.75 for the outer and inner bar, respectively. For the median grain size, d_{50}, the value 0.3 mm was specified. The dimensionless coefficients m (Eq. 5.6) and C_B (Eq. 5.7) were set to -0.5 and 0.08, corresponding to the optimal values obtained by Larson *et al.* (2016) when applying the model to different field sites. The water temperature was set to 15ºC. The initial bar volumes (t=0) were assigned to the initial observed values (calculated from the survey data), that is, 49.2 m^3/m and 16.2 m^3/m for the inner and outer bar, respectively. The empirical coefficient δ_0 was calibrated to 3, based on the observed typical relationship between the inner and outer bar volumes. The critical wave height H_c was assumed to be around 2 m for Duck beach. To test the model, two schematic cases were set-up by admitting (or not) exchange of material between the two bars.

6.1.3. Results and discussion

Figure 6.5 illustrates the inner and outer bar volume variation with time and the agreement obtained with the observations during the calibration and validation periods, when no sediment exchange between the inner and outer bar was considered. The optimal parameter values found for 1981-1985, including the multiplier C_c for both bars, were used in the validation during 1985-1989.

Overall, promising results were achieved for the calculated outer bar volumes, yielding a least square error of ε=0.39, though the scatter obtained during the validation period was significantly larger compared with the calibration period (see Figure 6.5). For the representative total volume stored in both bars, trends in volumes were reproduced showing a good initial agreement between the two series, but developing discrepancies towards the end of the validation period, corresponding to the time when the outer bar decayed and the inner bar experienced offshore migration (with only one bar appearing). The same is verified for the outer bar volume, with the largest deviation occurring during the summer of 1989, when the inner bar moved seaward as a result of the storms hitting the beach during the winter of 1988/1989. Also, mainly during Sep-89, the wave periods were considered unusually long (with an average and maximum value of 10.6 s and 23.3 s, respectively) and judged to be outside the range for which the estimated parameter values would be applicable. Thus, some events towards the end of the validation period should not be included in the comparison. It should be emphasized that the model confines the outer bar growth to high-energy events, for which the input critical wave height assumes a central role (H_0>H_c). This site-specific parameter describes a change in the forcing conditions characterized by a stronger net seaward movement that would act as a trigger for the onset of the outer bar formation.

Due to the considerable scatter in the observations of the inner bar volume, demonstrating a quite random behavior, part of the data were poorly reproduced, with a computed least square error ε=0.55. This may be attributed to the fact that the inner bar is typically located within the region of breaking waves, where profile changes are more irregular and with a rapid response, challenging the predictive capability of the model. Limitations on the predictability of the inner bar behavior were also recognized by Splinter *et al.* (2018) when applying a simple equilibrium model to field data of observed sandbar position.

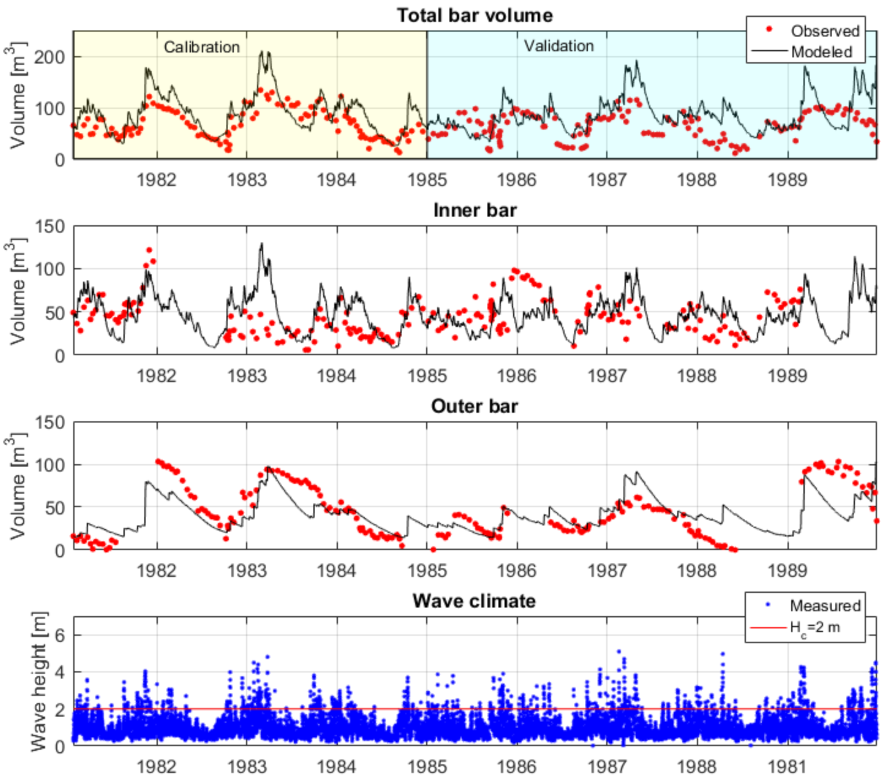


Figure 6.5. Total, inner, and outer bar volumes and wave climate (Duck, N.C.). Numerical simulations without considering sediments exchange between the inner and the outer bar.

Overall, comparing with the previous simulations, results including an exchange of material between the inner and the outer bar (Figure 6.6) produced the same main trends in bar volume change, but displaying changes in the inner and total bar volume, decreasing the least-square error to 0.51 and 0.46, respectively. The assumption that sediment transported to the outer bar are coming from the inner bar, tends to smooth things out, decreasing the amount of sediment mobilized in the subaqueous portion by the waves and reducing the estimated amount of sediment being transported through the interface between the berm-bar region. Although a scatter is still noticeable for the inner bar volumes, the trends for total bar volume are reasonably well described, with the predicted sum of the calculated bar volumes approximating the measured values. Thus, the exchange of material between the bars yielded improved agreement.

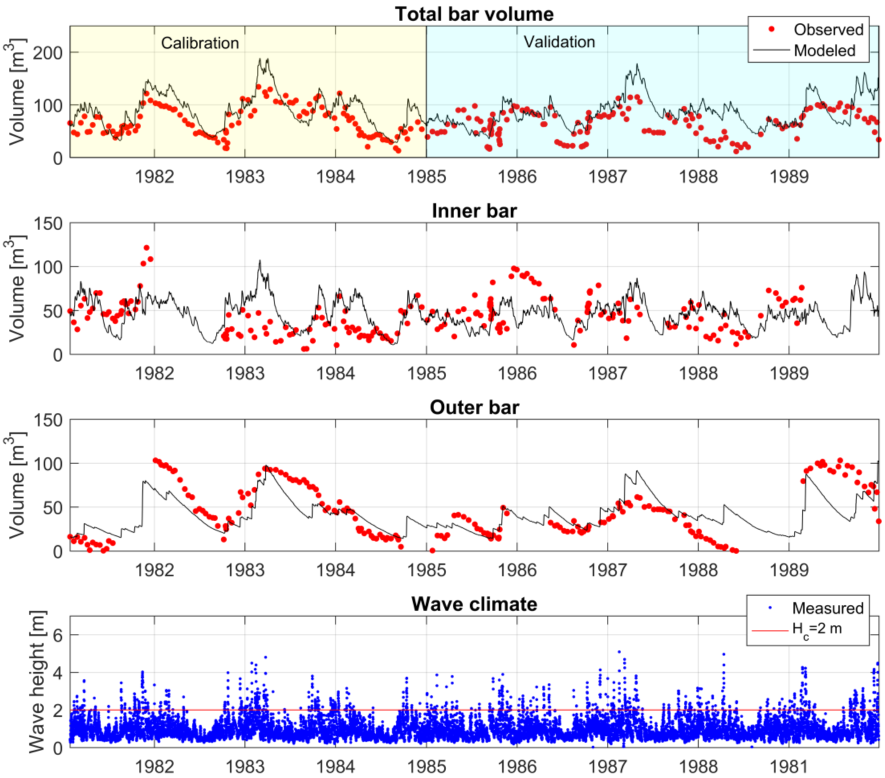


Figure 6.6. Total, inner, and outer bar volumes and wave climate (Duck, N.C.). Numerical simulations considering sediment exchange between the inner and the outer bar.

6.2. Silver Strand, California, USA

6.2.1. Background and data employed

The developed model for estimating the response of artificial nearshore bars intended to perform as feeder berms is here employed for reproduction of a field experiment carried out at Silver Strand, San Diego, California. During Dec-88, dredged material, removed from the outer portion of the channel entrance to San Diego harbor, was placed in the nearshore zone off Silver Strand State Beach (located approximately 7.5 km southeast of the dredging site) as a means of supplying the beach and preventing further erosion. The inlet-dredged sand was disposed at the top of an existing bar, between water depths ranging from -3 to -9 m MLLW (Mean Lower Low Water), in the form of a rectangular berm with dimensions approximately 360 m alongshore and 180 m across shore, and an average relief around 2 m. The estimated dredged amount was about 113 000 m^3, corresponding to an incremental cross-shore volume of 310 m^3/m of shoreline. The berm was composed of medium sized sand (d_{50}=0.18 mm) according to Juhnke *et al.* (1989), whereas the median grain size of the native material was approximately 0.25 mm.

After disposal, a follow-up program was set up to monitor the offshore mound response. Repetitive cross-shore surveys covering the placement area were performed during almost one year after the project was completed (from 9-Dec-88 to 15-Nov-89). In total, 9 field campaigns were carried out for 7 profiles (P1 to P7), in which four lines covered the initial location of the fill, and three were located southward. From the 9 campaigns, one was carried out just before (9-Dec-88) and one just after (29-Dec-88) the nearshore berm construction. These data have been earlier analyzed by Juhnke *et al.* (1989; 1990), Andrassy (1991), and Larson and Kraus (1992). According to Larson and Kraus (1992), who examined in detail several properties of the offshore bar through extensive profile data analysis, all the survey lines located across the placement site displayed similar behavior. Since Line 5 was located in the middle of the mound, where end effects caused by longshore transport should have been minimal, this line is used here in the model application. Figure 6.7 plots the surveys collected at Line 5 during the first completed year after the mound construction.

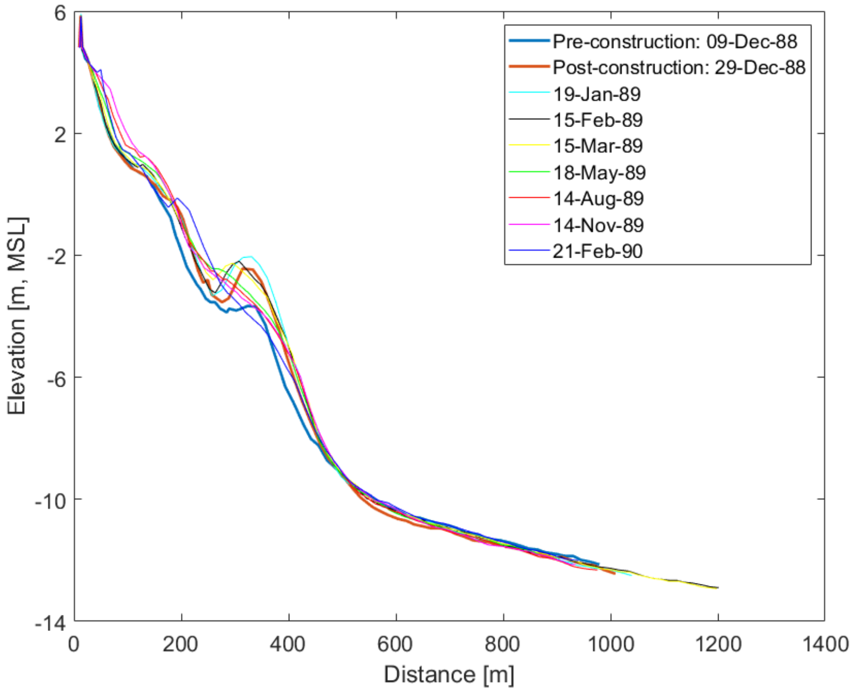


Figure 6.7. Surveyed profiles at Line 5 (during first year after berm construction).

Figure 6.8 displays the evolution of some nearshore bar properties (volume, maximum height, and depth to the bar crest) determined by Larson and Kraus (1992), by comparing the surveyed profiles with a derived equilibrium profile (obtained through least-square fitting of an equilibrium profile to the pre-construction survey).

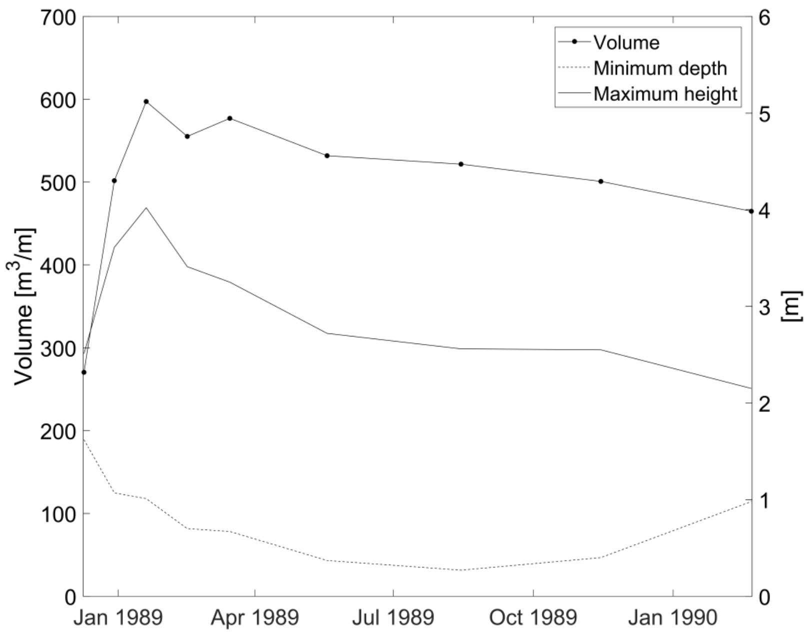


Figure 6.8. Evolution of the offshore mound properties with time (volume, maximum bar height and minimum bar depth). Depths refer to MLLW (= MSL - 0.85 m).

Overall, the profile change analysis indicated that the offshore mound has suffered a decrease in volume and height, as the bar flattened out and migrated landward during the measurement period (see Figure 6.8). Larson and Kraus (1992) noted a general shoreward displacement of the mound center of mass, whereas the length of the berm showed an increase at first, thereafter followed by a slight decrease. The minimum depth at the mound firstly decreased, as the mound moved onshore, filling up the trough, afterwards exhibiting a slight deepening (see Figure 6.8). As shown in Figure 6.8, after the fill placement, the maximum bar height increased rapidly, but after about 5 months a constant value was approached, indicating that the bar primarily flattened out during this period – note the significant reduction in berm relief from 4.02 m (Jan-89) to 2.72 m (May-89). Although less marked, the volume change follows the same trend as the observed bar height, reaching its maximum in Jan-89, with almost 600 m^3/m. The increase in material occurring between 29-Dec-88 and 10-Jan-89 derived from clean-up dredging and disposal operations that were still conducted during this period as a result of a couple of hot spots remaining in the channel. It was estimated that approximately 7 650 m^3 of sand was dredged for that purpose. However, according to Andrassy (1991) the highest fraction of the deposition registered between the post-construction and the following survey was likely related to some accretion of sand moving alongshore as a result of the creation of a relative low energy area in the lee of the disposal site.

Andrassy (1991) computed the volume change in three elevation zones (3 m to 0, 0 to -3 m and -3 m to -10 m MLLW) in relation to the pre-construction bathymetry and observed a direct transfer of material from the original mound area towards the +3 m to -3 m MLLW region. Evidence from the surveying suggests that the flattening and onshore migration of the berm contributed to accretion of material along the inner portion of the profile.

6.2.2. Model set-up and calibration

The empirical approach described by Eq. 5.21 was adopted to simulate the evolution of the mound created off Silver Strand State Park, for the time period of 9-Dec-88 to 21-Feb-90. The input profile was schematized based on the pre-construction survey carried out in 9-Dec-88. In order to investigate model performance two schematic cases were set up: 1) simulating the fill operation due to instantaneous addition of material to the existing bar volume (inner), adjusting the bar response rate with respect to the general response of the mound; and 2) modelling a representative morphological volume of the inner portion of the profile (described by V_{BE}^{I}=0), so that a transport of the fill material towards shallow depths, deriving from the flattening and onshore bar migration process, could be reproduced. Since wave measurements in connection with the surveys were only available for a limited time period (between 20-Jan-89 and 18-May-89), hindcasted wave data were employed in the simulations for the missing period. The model time step was set up based on WIS (Wave Information Studies) wave information, available every 3 h. The initial bar volume, $V_{B,initial}^{I}$, was set to the measured value of 270 m^3/m at 9-Dec-89. Also, an extra cross-sectional fill volume of 71 m^3/m was added to the simulations to represent disposal operations and longshore volume variations that occurred between 29-Dec-88 and 19-Jan-89. The median grain size of the fill material was somewhat finer that the native sand (0.25 mm) along the nourished portion of the profile, so a value of 0.20 mm was adopted for d_{50}. This value was also used by Larson and Hanson (2015) when modeling mound diffusion at different sites (including the Silver Strand site) using a one-dimensional diffusion equation. The water temperature was specified at 15ºC, and the same values on m and C_B from Duck were used for Silver Strand. The values of the remaining site-specific input parameters were mainly determined by comparing results and trends of changes in bar volume in order to obtain the lowest value on ε for both schematic cases. The optimal value on λ_0 that yielded to the best agreement between the measurements and model results was 0.002 h^{-1}, whereas for C_C a value of 0.10 and 0.20 were considered for the first and second case, respectively. Based on the average value of the minimum depth to the bar crest, in the latter case, a wave breaking height H_1=0.8 m was specified to identify events when sand is transported onshore across the inshore portion of the profile.

6.2.3. Results and discussion

The bar transport model was successfully employed for the one-year simulation period, as the pattern of landward migration of the offshore mound could be reproduced for the studied profile. The results of the simulations are here presented and evaluated by comparing the computed bar volumes with the values on the offshore bar volume estimated from surveys (see Figure 6.9 and Figure 6.10).

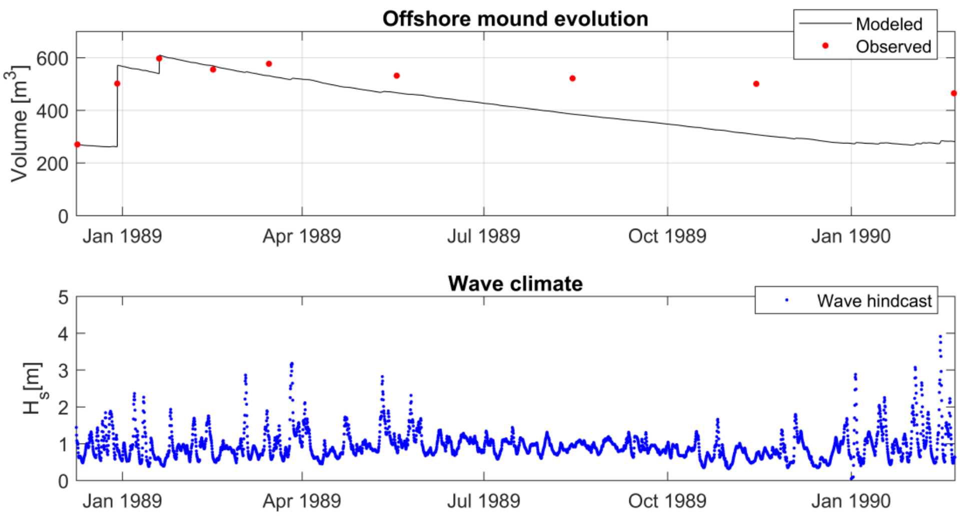


Figure 6.9. Nourishment evolution simulation by adding extra volume to the existing bar (Silver Strand, Coronado).

Figure 6.9 displays the simulation results obtained when directly adding material to the existing bar. As seen in the figure, discrepancies develop towards the end of the simulation period, as the measured bar volume exceeded the predicted values. The computed error was ε=0.26, with an error for the last four data points computed in ε=0.30. The observed data points indicate that a large part of the fill material still remains at the site placement area, revealing that the model release the fill material from the bar towards the beach somewhat too quickly. The onshore transport of material captured by the surveys, exhibiting a gradual lowering of the maximum bar height as well as an increase of material in the inshore portion of the profile might be a possible reason for obtaining these deviations (see Figure 6.8). In fact, in the numerical model simulations, the fill material is transported by the waves directly to the beach (decay in the bar implies a growth of the beach width), which is not in agreement with the observations, since part of this material appeared to go through the surf zone before ending up on the beach.

Figure 6.10 shows the model results when simulating a hypothetical inner feature to better account for the transfer of material across the surf zone.

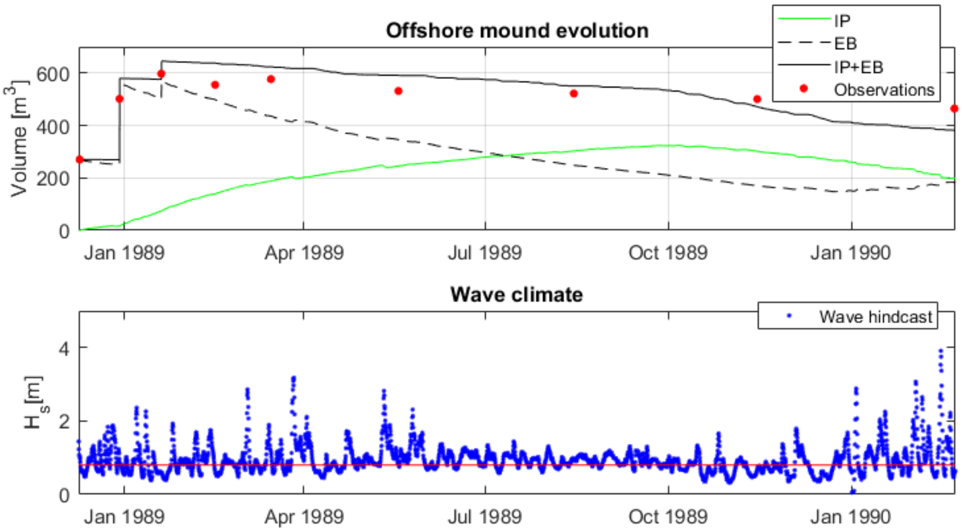


Figure 6.10**.** Nourishment simulation using a hypothetic inner bar (Silver Strand, Coronado), where IP and EB are acronyms for Inshore Portion and Existing Bar (nourished with dredged material), respectively. Red line represents a threshold for the wave height that controls when sand is transported landward, from the inner portion of the profile to the berm (H_1).

In the previous figure, the natural evolution of the nourished bar is represented by the continuous black line (computed with respect to its equilibrium state). The green line represents the evolution of the hypothetical feature which depends on low-energy events

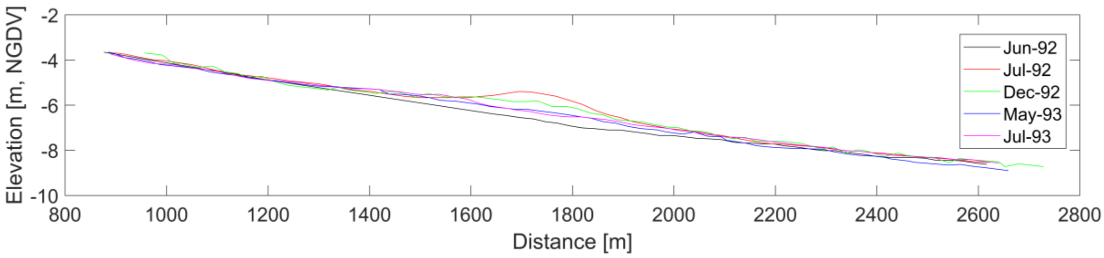
($H_0<H_1$) to transport the fill material to the beach. The dashed line corresponds to the sum of the modeled values for the inner portion volume and the nourished bar volume. Although the surveys have indicated a mixed response between the existing bar and the fill volume (moving as an unique identifiable unit), the calculations demonstrate that simulating the impact of flattening mound process by incorporating a hypothetical inner feature produced significant improvement, especially during the final part of the study period where measured and modeled values agree well, yielding a lower total error of ε=0.18. Also, the trends are satisfactorily described, making a better reproduction of the measurements than in Figure 6.9.

6.3. Cocoa Beach, Florida, USA

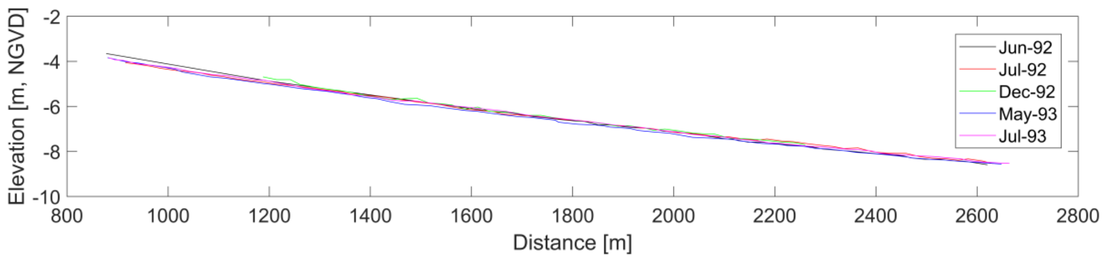
6.3.1. Background and data employed

In the Silver Strand case, the simulations of the underwater nourishment response (*e.g.*, through the modelling of a hypothetic bar, defined as V_{EQ}=0) were performed for coastal systems where natural bars frequently appear. In order to simulate coastal systems where no longshore bars were monitored during the surveyed period, the same procedure can be adopted. As the formation of longshore bars is the natural profile response to storms (*i.e.*, large breaking waves), for such coastal systems the volume change in the subaqueous portion of the beach profile may be significantly lower when compared to systems that exhibit such impact. This behavior can be described by V_{BE}^{O}=0 m^3/m together with V_{BE}^{I}=0 m^3/m, if also the inner bar is absent.

Here, the model applicability in predicting the evolution of a sand bar artificially implemented at Cocoa Beach (Florida, USA), a coastal area characterized by the absence of natural breaker bars, is demonstrated. Dredged sand from 1992-1994 maintenance activities at the Port Canaveral Entrance channel was placed in a nearshore disposal area offshore of Cocoa Beach (8.4 to 11.3 kilometers southward of the source), in order to retain beach-compatible sand in the littoral system. The intent of the federal maintenance dredging project, involving disposal of the dredged material downcoast, was to minimize local beach erosion (mainly attributed to the presence of the inlet), by constructing a shore-parallel bar within the active littoral zone that directly or indirectly could benefit the shoreline. The fill activities started in 1992 (from 6-Jun through 24-Jul), involving the deposition of 121 000 m^3 of sand. In 1993 and 1994, more disposal activities were undertaken, implying a total sand volume mobilized of around 263 000 m^3. Although bathymetric data were collected to document the evolution of these interventions, surveys covered different areas along and across the shore. Thus, after data censoring, just a specific set of high-quality monitoring data, related to the first intervention (1992), were selected for model application. This data set encompasses five bathymetric surveys collected for several lines alongshore, spaced about 40 to 75 m apart, intercepting the placement site. These lines were surveyed before (pre-project, Jun-92) and after the fill placement (post-project, Jul-92) and then, on three different occasions, until one year after construction was completed (Dec-92, May-93, Jul-93). The data collection extended from 45 m seaward of the disposal area to about 245 m landward thereof, or from the -9 m to -4.0 m (NGVD) depth contours. According to Bodge (1994), the permitted nearshore disposal area of 1992 was defined as 2 895 m in the longshore direction and 200 to 245 m wide in the cross-shore direction. Figure 6.11 depicts the surveyed profiles along two distinct lines: one located in the northern part of the designated placement area; and the other in the southern part, where no fill material was placed during the first disposal.



a) Line located at 150 m.



b) Line located at 1525 m.

Figure 6.11. Selected survey profiles intercepting the permitted disposal area (0 m to 2 895 m in the local alongshore coordinate system): (a) northern part and (b) southern part.

Although the authorized disposal area extended alongshore from station 0 southward to station 2895 (0 m to 2895 m in the local alongshore coordinate system), inter-survey data analysis along this area showed that the nourishment activity took place in the north, from station 0 to about 815 m southward. This is in agreement with Figure 6.11, where the seabed changes of the most northern-located profile (Figure 6.11a) demonstrates that the initial bar was constructed here, while no pronounced bar is observed in the southern disposal area (Figure 6.11b). Thus, since the nourished sand was not uniformly distributed alongshore in the permitted dumping area, six northern evenly-spaced profile lines were selected to evaluate the seabed changes associated with the nearshore berm. For each survey event, the average depth of these six profile lines (intercepting the disposal activity) was computed. The evolution in time was thereafter compared within the same cross-shore surveyed area. Since the first survey was carried out before the fill placement, the corresponding average profile was designated as the “background” (or “pre-project”) profile. Figure 6.12 plots the average profiles computed for each survey event that occurred between 16-Jun-92 and 1-Jul-93.

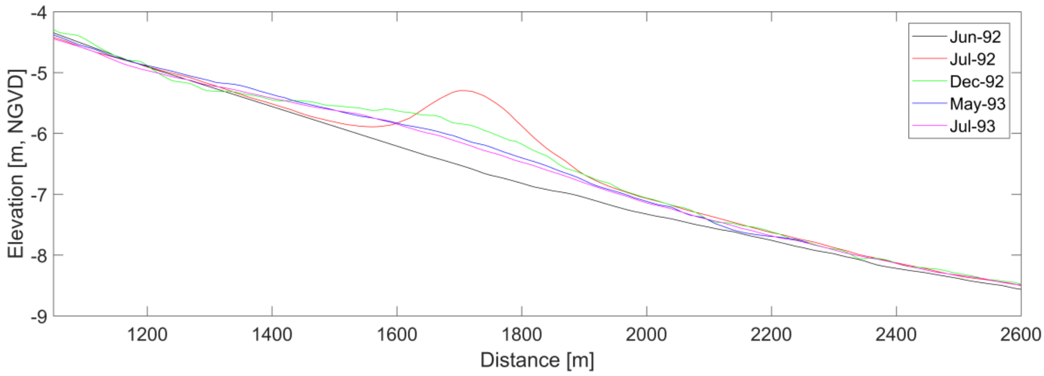


Figure 6.12. Average profile evolution at northern disposal area (0 m to 800 m). Distance along the profiles refers to an artificial baseline set at approximately the NGVD shoreline.

In Figure 6.12, an artificial nearshore bar can be recognized just after the placement (Jul-92), as well as a subsequent pronounced landward migration of the mound during the following months (Dec-92; May-93; Jul-93) accompanied by a clear shift of the berm crest towards shallower waters. Also, the bar height experienced a significant reduction during the first 5 months after the dredged material was placed, corresponding to the period when most of the flattening occurred. Thereafter, the bar relief decreases more slowly, with the bar almost welding on to the shore in Jul-93. Overall, the onshore movement of the artificial berm resembles a cross-shore diffusion process, influenced by a shoreward-directed advection. Thus, it is observed that the flattening and onshore movement of the mound contributed to the accretion of material along the inner portion of the profile.

6.3.2. Model set-up and calibration

The model was run for a year from 16-Jun-92 to 01-Jul-93. As in Cocoa Beach, no natural bars were monitored, the numerical model was set up to reproduce the behavior of the nearshore berm disposal through the simulation of a hypothetical feature defined by $V_{BE}^{O} = 0$ m^3/m (representing the outer portion of the profile). In line with the Silver Strand study case, to improve the agreement with the observed mound response (Figure 6.12) and to better reproduce the transport of the fill material through the surf zone, a representative morphological volume for the inshore area was included in the simulations. This morphological feature, included to describe the exchange of material between the subaqueous berm and shallower portions of the profile, was considered to behave in the same manner as the outer bar, implying a second threshold value for the wave breaking height, H_{b2}, intended to control the nearshore activity. Both equilibrium volumes are set to be zero and thus, this exchange of material is considered to be onshore-directed. Since no wave measurements were made in connection with the profile surveying, a wave hindcast with a 3-hour time step was used in the simulations. Model calibration was performed by adjusting site-specific input parameters and estimated values based on the pre-surveyed profiles and previous studies.

According to Bodge (1994), the median grain size of the pre-disposal seabed was 0.104 mm, whereas samples of seabed during and after the disposal activities indicated a representative median diameter around 0.40 mm. As the native grain size differed significantly from the nourished sand, an average value of 0.21 mm was adopted for d_{50}. The water temperature was specified to 26ºC. The same parameters values on m, C_B and λ_0 used for Silver Strand were kept for Cocoa Beach. The optimal value on the multiplier (C_C) employed to reduce λ_0 was 0.2. Wave heights thresholds of 4.2 m (H_{b1}) and 2.0 m (H_{b2}) were specified to determine onshore movement of material from the outer and inner portions of the profile, respectively, for periods when the offshore wave height does not exceed these values. To validate the model, comparisons were made with measured profiles.

6.3.3. Results and discussion

The model results were quantitatively evaluated by comparing the computed bar volumes with the values estimated from the surveys. Figure 6.13 depicts the time variation in the calculated bar volume, as well as the agreement obtained between the measured and the predicted values during the first year after nourishment operations.

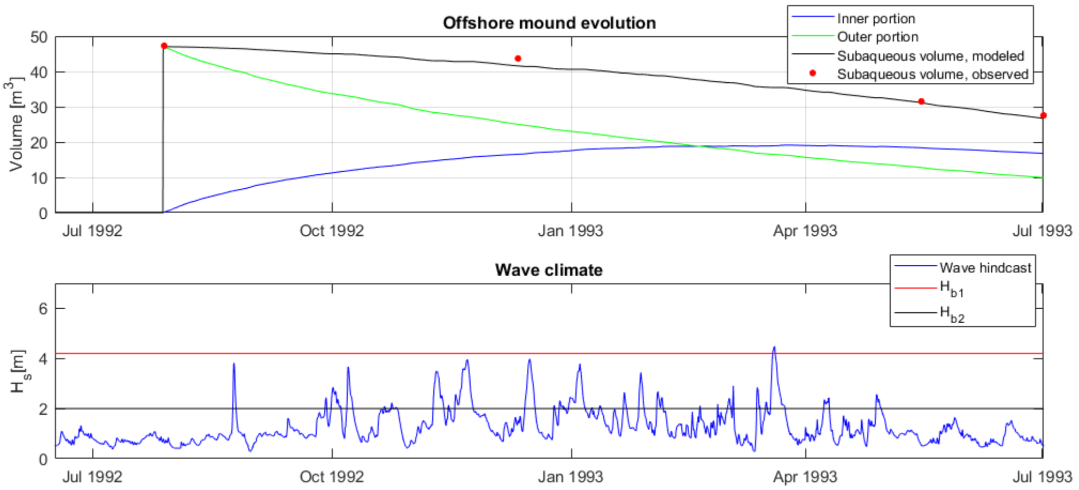


Figure 6.13. Results of the nourishment simulation using a hypothetic outer bar (Cocoa Beach) considering exchange of material with the inner portion of the profile.

The model prediction is judged to be good by considering the transfer of fill material towards the shore through the most inshore portion of the profile. The obtained error was ε=0.03. At the same time as the outer bar started to release sediment, the inner portion filled up as the wave forcing was favorable for such conditions (note that the wave climate was quite energetic during this period). A shift towards low-energy wave conditions (reflected by a general decrease of the values of H_s) appearing simultaneously with the maximum inner volume (Apr-93) suggests a change to a negative sediment budget at the inshore part of the profile, where the volume transported from the outer zone to the inner becomes lower than the volume transported from the inner portion to the beach (see Figure 6.13). This behavior is in agreement with Figure 6.12, where the major modifications of the mound shape took place during the first 5 months just after the fill placement (between the “post-survey” and Dec-92), while during the next period (Dec-92 to May-93) a higher volume loss occurred. Overall, the time adjustment of the profile towards an equilibrium state is being properly described by the model, as well as the volume time variation during the measurement period.

6.4. Summary

Chapter 5 has introduced an extended version of the heuristic model, first introduced by Larson *et al.* (2013) and designed to calculate bar-berm material exchange for application in coastal evolution models that describe processes at the decadal scale. The model was enhanced to reproduce the overall shift in material between the bar system and the berm of the profile by taking into account the long-term evolution of multi-bar systems and the response of offshore mounds placed for beach nourishment purposes.

The model was calibrated and validated in standalone mode at three field sites from the United States: 1) Duck, NC, where two natural longshore bars (an inner and outer bar) typically form; 2) Silver Strand, CA, where a nourishment was placed on top of an existing bar; and 3) Cocoa, FL, where an offshore bar was located in deep water where no natural bar was found. It was shown for the Duck case that the response of the outer bar was significantly slower than the inner bar to changes in the cross-shore sediment transport. Thus, non-dimensional multipliers (or coefficients) in the empirical transport relationships had to be determined based on the data. Overall, equilibrium volumes and rate-of-change coefficients were related to non-dimensional wave and sediment properties (*i.e*., wave steepness and non-dimensional fall speed), but during the calibration certain coefficient values had to be obtained through comparison with data and subsequently validated. Although the criteria presented in 5.5.1 and 5.5.2 should provide a first rough estimate of suitable values, parameters such as the critical wave height and wave breaking height (used to define the wave heights thresholds) determining the outer bar formation and the response of mounds, respectively, are expected to be site-specific and data are needed to apply the model with confidence at a particular site.

One of the challenges at understating and predicting multi-bar behavior was the book-keeping of individual bars. The low temporal resolution of the data employed for Silver Strand and Cocoa Beach case studies (approximately one year) was also considered a limitation to this study. Modelling of multi-bar systems is complicated when bars merge and migrate both in time and cross-shore. Bar merging is more common during transition periods (winter-summer or summer-winter) and also linked to nourishment operations. Bar migration has been mostly linked to situations with severe surf zone conditions promoted by high-energy events. Such mechanisms are expected to impact the bar behavior. However, the cyclic behavior of barred systems (happening on the time scale of years) was implicitly accounted since a growth in the outer bar volume is associated with a net seaward movement of sand and a decay in the outer bar volume is caused by onshore sediment movement (tending to degenerate the outer bar). The model treats each bar as a discrete entity, allowing also feedback from adjacent features, although the migration of individual bars is not captured by the model.

Despite these shortcomings, the model application showed that the equilibrium model is skilled at predicting the time-varying volume of the outer bar, suggesting that this morphological feature is strongly influenced by offshore wave forcing in a predictable, equilibrium-forced manner (ε=0.39). Model skill was lower when predicting the inner bar evolution due to the scatter of the observations. It is yet to be explored if the inner bars in a multi-bar sites display predictable, equilibrium driven cross-shore behavior, similar to outer bars and shorelines. As discussed previously by several authors (Splinter *et al.*, 2018), the behavior of the inner bars is hypothesized to be more conditioned by changes in the tide range and act as sediment transport pathways between the shoreline/berm and the outer bar.

Overall, the present chapter demonstrates the potential for using rather simple models, underlying the definition of some equilibrium state that is compared to the current state and some magnitude of forcing available to drive the changes in the profile. The methodology employed here allowed to quantitatively reproduce the main trends in the subaqueous beach profile response in a long-term perspective as a function of the bar volumes disequilibrium and magnitude of the incident wave height and the dimensionless fall velocity to move the sand with a time-varying forcing term outside the disequilibrium term. Duck measurements have detected that some bars form in the nearshore and move all the way offshore (eventually deflating by non-breaking waves). At the same time, it was equally observed that a lot of inner bars form in shallow water do not move offshore, but remain as inner bars all the time. According to this, the developed model considers that the inner bar will not become the outer bar, but material previously dedicated to the inner bar will be available for the outer bar.

It was also shown that the model has applicability for predicting the evolution of nearshore mounds that migrate towards the shore and become part of the beach face by the action of waves and currents, through the simulation of hypothetical bars defined by zero equilibrium bar volume. This modelling approach could be more widely applied to other beaches to explore shoreline equilibrium behavior, by merging it with a shoreline evolution model, or combining it with a compatible dune erosion module to simulate beach berm response and illustrate its applicability in predicting seasonal changes, as well as the supply effects at medium-term related to the fill project on the shoreline position.

CHAPTER 7

FINAL REMARKS

Chapter structure

7.1. Conclusions

7.2. Future developments

7. FINAL REMARKS

Over the course of this dissertation, monitoring and modelling approaches established in connection with artificial sand nourishment projects were in focus. Also, as a part of this research project, governing processes affecting the evolution of the Portuguese littoral as well as the legal structure in which its management system is built on were critically reviewed, and the potential contribution of the monitoring programs to identify challenges in coastal planning and management explored. This chapter corresponds to a summary of all the research work developed during the PhD studies, presenting the main conclusions drawn throughout this dissertation, as well as potential future research developments.

7.1. Conclusions

This section aims to give emphasis to some of the aspects considered of major relevance in the development of the various chapters composing this dissertation. After the first chapter, where the background and the motivation of the present study are stated, five chapters were developed. The main findings standing out from each chapter are here compiled and highlighted as an attempt to address each specific objective formulated early in Section 1.2. The scheme presented in Figure 7.1 gives a general overview of the scope of the different chapters and how they arise and interlink around a central thread for achieving new and relevant research contributions.

The understanding of the *status quo* of coastal erosion, as well as the causes and features of the Portuguese eroding beaches were given in Chapter 2. Results of the review of the documented coastal evolution in Portugal have evidenced as the erosion process has been boosted by natural factors and aggravated directly and/or indirectly by human-driven factors (*e.g.* dam activity, poor land-use control, harbor activities and manmade coastal structures). In the last years, due to the generalized erosion situation along the Portuguese coast and the debate generated around the secondary effects or negative impacts of hard engineering structures on downdrift erosion, the national guidelines for coastal protection have been demonstrating a “paradigm shift” (see Figure 7.1). Soft coastal protection solutions are now being regarded as the preference method to combat erosion and to achieve the desired protection of the coast. At the same time they “promise” opportunities for recreation and nature-based activities, opening a space for “sustainability”.

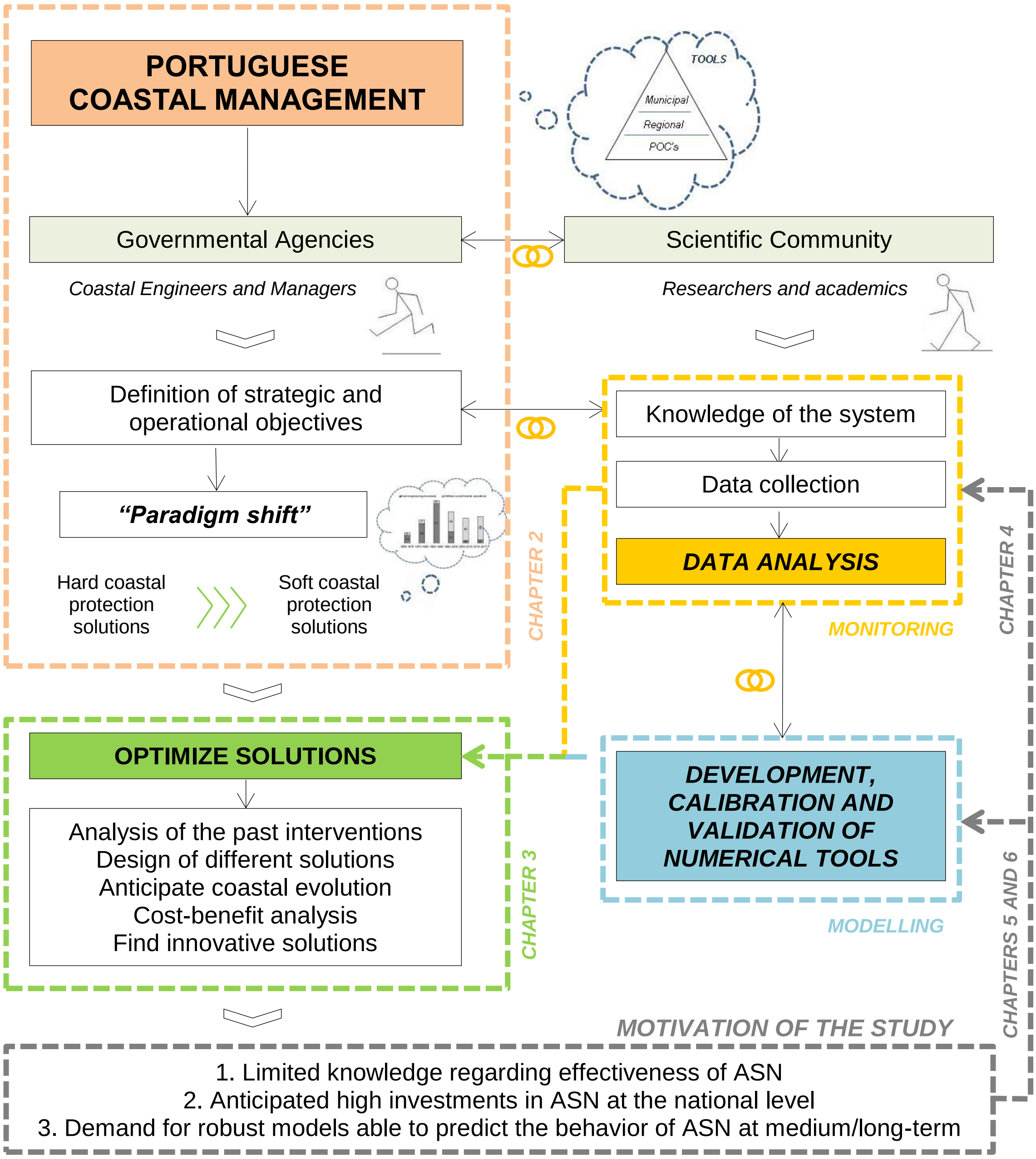


Figure 7.1. Scheme-resume of the PhD studies (ASN= Artificial Sand Nourishments).

Vulnerability and risk of the Portuguese coastal zones were also briefly reviewed, where it became clear how the northwest coast of Portugal have been suffering from a scarce sediment input (mostly attributed to the weakening process of the alluvial sources) and a high-energy wave climate, which turns this coast into one of the most active in terms of sediment transport fluxes (Santos *et al.*, 2017). The Espinho-Torreira coastal stretch is considered one of the most exposed and vulnerable areas to erosion, presenting one of the highest erosion rates (COSMO, 2016). In the order of priorities for nourishment purposes, this stretch was taken nationally to a first level due to the intensity of the ongoing erosive process and its privileged location, at the northern boundary of the sediment circulation cell, providing potential for feeder response of the nourishments to downdrift coastal stretches.

The legal status and policy on coastal management in Portugal was equally examined by looking at the administration system, legislation and regulation, as well as the policy tools scheme, built into the legal structure with different levels of hierarchy (Figure 7.1). Although, over the past few decades, coastal engineers and managers have been trying to bring into practice the concept of Integrated Coastal Zone Management (ICZM), some political and social challenges still remain. These challenges derive mainly from the lack of a cohesive management structure able to cover the full cycle of information collection, planning, decision-making and monitoring. Facts like low participation of the stakeholders, lack of coordination between parties, lack of up-to-date and systematic information databases (usually dispersed among different institutions) as well as limited public financial resources devoted to coastal protection, allied to the monopoly kept by the governmental agencies regarding all aspects of the coastal zone, constitute the major challenges to the definition of strategic and operational objectives in an attempt to achieve sustainability.

The overview performed over the Portuguese coastal management system has particularly stressed the importance/necessity of exploring all kind of issues related to the behavior of artificial sand nourishment (ASN) projects in order to maximize the benefit taken from these operations – set an optimal solution for the Portuguese coast – also in response to the increasing capital investment that has been anticipated by technical and scientific experts behind governmental agencies. The *working with nature* concept was introduced in Chapter 3 as a mean to address the sustainable character that usually appears in connection with the ASN projects. Their general performance and related costs, benefits and impacts were briefly discussed. A review of the artificial beach nourishment experiences in Portugal was also addressed in Chapter 3. In total, 97 past interventions of ASN projects (summing up to more than 20 Mm^3 of disposed sand) were set in a historical perspective (over the last 20 years) and discussed under the light of different criteria: specific objectives, sediment sources, fill placement techniques and responsible entities for carrying out the projects. Main findings pointed out that 87% of the nourishment interventions were mostly engineered for advancing or holding the shoreline position and/or increasing the beach width, whereas only 13% were designed for reducing vulnerability to overtopping/flooding, protecting hard coastal structures and/or protecting the natural/cultural resources, following this order of occurrence. Also, it was verified that for 67% of the total operations, the disposal activities have focused on the subaerial portion of beach (dune, berm or both), summing up to 74% of the total fill volume mobilized. It was also concluded that the government (Ministry of the Environment) and Harbor Administrations were the main responsible for performing 90% of the ASN projects. Harbor Administrations (HA's) also represent the biggest slice in terms of sediment borrow sources, "sponsoring" the majority of ASN interventions (up to 70%) with dredged sediments resulting from regular harbor maintenance or deepening activities. These meaningful results have highlighted how HA's play an important role in promoting ASN projects and the significant use of "sediments of opportunity" in Portugal, whose primary goal is not beach nourishment. Continental platform (offshore) has appeared as the second most representative borrow source, providing 20% of the total fill volume, followed by inland deposits (also resulted from harbor activities) and bypass systems, with 9% and 1%, respectively.

Chapter 2 and 3 have made also clear that the economics and benefits referred to artificial beach nourishment projects are still under-researched, existing a gap between the useful information provided by scientists and the one demanded by decision makers. In order to be able to optimize protection solutions based on a scientific and technical basis, data collection programs must be encouraged and cannot be neglected. Monitoring data represent a mean to objectively document and assess the performance of the project, providing insights over the governing processes and consequently helping to formulate modelling requirements that can lead to the increase of the predictability and projection capacity of the evolution of the littoral (Figure 7.1). Simultaneously, anticipate how the coastal system may evolve necessary implies good knowledge and quantitative/qualitative understanding over the main components of the sustainable development: physical, social and economic. Such knowledge and understanding are still limited and sometimes produced by researchers, scientists and academics in a timescale not compatible with the operational management needs for dealing with numerous coastal problems, usually demanding a quicker response and action peppered by the engineering judgment and failing for the lack of a scientific basis.

Building on theses premises, a zoom-in was made over a regular-nourished coastal stretch (Barra-Vagueira coastal stretch, northwest coast of Portugal), located immediately south of the Aveiro harbor, and taken as the case study of the present dissertation. Chapter 4 was developed in attempt to assess the effectiveness of several nearshore nourishment interventions carried out between 2009 and 2015 in connection to regular Aveiro harbor maintenance activities. The study was built upon a monitoring data set collected to meet the main requirements given by Environment Impact Statement (DIA) – targeted to the Harbor Administrations, so they are allowed to conduct the dredging operations – with the prime goal to track the morphodynamic evolution of the disposal activities, as well as assess their impact to the adjacent coast.

The available data encompassed topo-hydrographic surveys for 12 cross-sections (with 1km spacing) distributed along the coastal stretch, on an annual basis, and bathymetric measurements collected for the dumping areas, annually, and just before and after nourishment operations. Considering the concurrent offshore wave forcing and all the effects of the nourishment operations, dominant temporal and spatial patterns, morphological changes, evolution trends, sediment budgets, and short- and medium-term responses of the fills, were investigated by the use of Geographic Information System (ArcGIS) tools and a multivariate statistical method based on Empirical Orthogonal Functions (EOFs). Overall, during the monitoring period, the study area has received almost 3 Mm^3 of sand - dumped in different locations and periods to control the erosion observed downdrift of the Aveiro inlet. However, bathymetric surveys and profile indicators still point out the erosional longshore pattern diagnosed decades ago for the coastal stretch under study, as a result of a negative longshore sediment balance.

Observations also revealed that short-term changes, arising from the seasonal cycles of cross-shore material exchange were mainly linked to the largest variations in the beach profile shape, also affecting the sediment budget. Profiling indicated cross-shore volume variations ranging from ± 250 m^3/m and ± 1500 m^3/m in the subaerial and subaqueous portion of the profile, respectively, along the monitored period. After the first completed seasonal cycle, the sand bar, artificially created by the nourishment, could not be visually detected in the profiles, suggesting a cross-shore redistribution of the fill material. For revealing patterns in data sets on beach morphology that are spatially and temporally sparse, the application of EOF analysis proved to be a weak tool, stressing the importance of high quality data to achieve adequate evaluations.

Overall, the set of correlated analyses exhibited in Chapter 4 have stressed the importance of establishing proper monitoring programs based on adequate surveying instruments and data collection strategies, in order to ensure high-density data that could be used in support to the decision-markers. Although it was possible to relate some changes in the beach morphology to the hydrodynamic forcing events, fill placements, and some sediment transport mechanisms, the limited set of conclusions drawn have raised the question about the suitability of the monitoring surveying approach recommended in DIA, as well as highlighted challenges in the Portuguese monitoring scheme that must be overcome in order to improve monitoring network and database building. A more systematic monitoring plan and comprehensive data collection, as well as the use of highly precise electronic surveying instruments, for collecting high-density data accurately and efficiently within a selected time, were considered fundamental in order to not compromise the follow-up studies and an accurate judgment of the project performance.

It was proposed to refine the monitoring programs, so they could include regular surveys throughout the year, including prior to dredging and periodically thereafter, as a way to capture important cross-shore changes and establish a solid coastal baseline as a reference for investigating fill responses, regarding time evolution and performance with a high level of confidence. Contingency plans for collecting surveys immediately after storms and site inspections concurrently with the profile surveying were also considered important, so that post-storm conditions of the project and storm-induced beach changes, as well as relevant information that could characterize the subaerial beach evolution (*e.g.* evidence of movement of the fill material, dune foot position changes) may be documented. Lastly, extending the monitoring of the dumping areas not only in the cross-shore direction (landward/seaward) but also alongshore, was encouraged for a better assessment of the feeding property of the operations. A higher spatial resolution of the surveying would allow obtaining detailed insights into the governing mechanisms and the forcing conditions that may affect the performance of the fills. This would also offer means of attempting to maximize the potential of nearshore accretion, providing a basis for developing guidance for engineers and managers regarding the best practices for sand disposal.

All the data limitations highlighted in Chapter 4 backed up the importance of developing and validating coastal numerical models, in particular, profile evolution models in support to the decision-makers, not only for giving assistance in the selection of optimal nourishment schemes, but also to investigate fill responses on a short-term and long-term basis. Under this light, suitable numerical approaches for simulating cross-shore sediment transport and long-term profile evolution were reviewed in Chapter 5. It presented a recent and innovative cross-shore (CS) evolution model with the capacity of modelling cross-shore material exchange and the resulting profile response at a decadal scale following a schematized approach compatible with coastal numerical models with focus on evolution at the regional scale. This model, designated as the CS-model (Larson *et al.*, 2016), has been further explored via one of its integrated modules – the bar-berm material exchange sub-routine – yielding to an improved CS-model.

The first version of the CS-model made possible to account for distinct and relevant cross-shore processes as dune erosion and overwash (impact of storms), wind-blown sand transport (dune recovery) and bar-berm material exchange (beach seasonality). These processes cannot be ignored when predicting the evolution of the beach-dune system for temporal scales up to decades and spatial scales on the order of hundreds of kilometers. The algorithm is based on a set of sediment transport equations detailing each one of the mentioned processes, which are then combined and solved together in combination with sand volume conservation equations, in order to compute changes in the profile shape. Such changes are modeled based on a schematization of the main morphological features of the profile and geometrically prescribed by the time evolution of a set of key parameters representing the dune, berm and bar regions (*e.g.* dune foot positions, berm position and bar volume).

In Chapter 5, it was detailed the first application of this model, where the cross-shore exchange of material and the resulting profile response was simulated for the period 2009-2013, for a selected section deriving from the case study previously in analysis in the Chapter 4 (Profile P6, intercepting the disposal site DA2, in Costa Nova beach). The results from this pioneer application revealed overall good performance as the observed profile response could be satisfactorily reproduced for the period 2009-2013, underlining the potential of the CS-model for predicting long-term evolution of beach-dune systems in a time perspective from years to decades, helping on the decision of the best protection approach to meet the strict engineering needs and environmental standards.

In the sequence of the successful test of the model against data from the field (Aveiro study case), a sensitivity testing, encompassing example applications deriving from hypothetical nourishment scenarios, mainly differing on the location, volume and frequency of the disposal sand, was also conducted in Chapter 5. Broadly speaking, the CS-model has driven to useful simulations detailing the gradual evolution of distinct fill design schemes in response to changes in the forcing conditions, and determining the time scale and redistribution of the fill material. Regardless the disposal site, simulations have evidenced that most of the nourishment schemes differed mainly concerning the time evolution of the profile adjustment towards a new equilibrium state, whereas the equilibrium states themselves were similar. Profile and bar nourishment schemes showed similar behavior, reaching quickly the same equilibrium states (typically after one seasonal cycle), whereas if the material was placed high up on the subaerial portion of the profile (dune nourishment scheme) it would take significantly longer time to adjust in comparison to other schemes, being the redistribution of the fill material restricted to the occurrence of severe storms with high water levels. The berm nourishment scheme also proved to have a protection effect on the beach against storms, as it reduces the probability of waves reaching the dune foot, preventing erosion. The sensitivity test demonstrated equally that after a specific nourishment volume, the profile does not benefit from an increased fill volume. Changing the frequency of placing sand does not have any significant impact on the final berm position. However, the concentrated approach set in the beginning of the simulation period showed to provide protection during a longer time period.

Fill design schemes were also discussed considering the purpose for which the project is designed. For example, whether it is engineered to increase dune robustness and strengthen the dune system over time - with berm nourishment being an appropriate solution - or to increase the beach width on a short-term basis, where the profile or bar nourishment scheme could be a potential solution. Dune nourishment could be faced as a medium/long-term solution since it depends on the occurrence of storms so that the fill material can be distributed along the profile, increasing the berm width until new equilibrium condition prevails.

Reports and descriptions of many wave dominated sandy coastal systems across the world have provided a basis for development of an extended version of the subaqueous cross-shore sediment transport model, having been equally useful to validate the module in a standalone mode (Chapter 6). The evolution of coastal systems consisting in two subtidal bars and the response of feeder mounds have been accounted through development of new theoretical procedures, later integrated in the subaqueous cross-shore sediment transport sub-routine. Efforts were directed to expand the theory for the evolution of a single-bar to a two-bar system, where the volumes of the individual bars and their responses can be modeled. The modelling was carried out for an inner and an outer bar, where the outer bar was considered of primary interest with the purpose of predicting the behavior of placed dredged material. The wave-driven cross-shore transport rate is based on the evolution equation for the bar system response to the hydrodynamic forcing by reference to its equilibrium condition, where the change in the bar volume is based on a set of wave criteria describing the onset of a new breaking zone, when the outer bar forms. Empirical formulas were employed for the bar equilibrium volume and for coefficients determining the bar response rate.

In Chapter 6, the model was firstly calibrated and validated against data from Duck, North Carolina, USA, where two bars typically appear. Field data derived from nearshore sand placement projects (Silver Strand State Park, California, and Cocoa Beach, Florida, USA), involving the construction of artificial longshore bars, were also employed to test the model in complex situations with diverse wave climates and typical beach profile shapes. One of these examples (Cocoa Beach) illustrated the application of the model to reproduce the evolution of an artificial bar placed in the nearshore area, where no natural bars have been recorded during the surveyed period. Descriptions of the coastal evolution from reliable sources (previous studies), as well as surveyed bathymetric data collected for each site were equally useful to calibrate the model parameters and validate the results. Overall, outputs of the application of the model to these three US case studies, look promising, as the time evolution of the submerged bar volumes, as well as the cross-shore material exchange could be satisfactorily reproduced for the selected application sites, showing good agreement between the simulated and observed values available for each site.

Aiming the improvement of understanding and predictability of the beach morphology change in a long-term perspective, this thesis was developed to constitute a step forward the increase of knowledge in the topic of artificial nourishments, serving to support coastal engineers and managers at the decision-making.

7.2. Future developments

This dissertation made clear that a continuous source of information and data collection is the key for a good understanding of the coastal morphodynamics, offering also a mean to calibrate and validate mathematical models, which are indispensable tools to predict changes in the coastal marine environment and the design of potential solutions for protecting the littoral. This will make easier a reasoned and timely action in the decisions involving the coastal zones. Unfortunately, availability of data constitutes a critical factor for the scientific progress. This was also the major limitation faced during the PhD studies and more than being faced as an excuse not to act, this situation serves to encourage the multiplication of monitoring programs/initiatives and studies for exploring functional relationships between the coastal dynamics and the wave climate.

Most of the research work covered in the present dissertation was developed around a central topic, the evolution of artificial sand nourishment projects from an engineering point of view. However, there are still numerous related research questions that could not be reached, either due to the poor information obtained from available sources and/or disabilities presented by the numerical tools. It is recognized, for example, that in cases where the nourished sand has grain size characteristics that are much different from the native beach, the nourishment may distinctly impact the natural response of the beach (Gravens *et al.*, 2003). Actually, the definition of the grain size distribution for the entire cross-shore beach profile is already a very complex theme since along the profile it is common to observe systematic variations in the median sediment grain diameter (d_{50}). Most often, the grain size is seen as a critical design parameter in numerical simulations, since models are not typically designed to handle different d_{50}, preventing to take into account the effect of using material with different size properties in case of beach nourishments. Indirectly, the selection of compatible fill material with the native sediments maximizes the accuracy of the model predictions of the future project performance, which is often based on past interventions responses for calibration purposes. However, the choice of the nourishment material is not only conditioned by a particular design objective (*e.g.* coarser-grained fill material to improve resistance to erosion), but also by limitations on sand availability and/or distance to the dumping site (and consequently related costs), becoming the discussion of the effect of the sediment properties considering different physical settings fundamental from the engineering point of view.

Another prominent aspect related to the design of nourishment projects is the adequate season to carry out the fill activities. From an operational standpoint, before the summer would be a suitable season to avoid a delay on the start of the bathing season. However, in cases that the fill material has very different grain size properties, even when recreational goals are not the main purpose, the aesthetics of the beach could be compromised, turning the beach unintentionally less attractive to tourists and bathers, consequently impacting the local economy. It is known that the economic value of the beaches, particularly those dedicated to public recreation, is intrinsically related to the aesthetics of the beach. Changing the natural landscape could put this huge resource at risk. On the other hand, operating the fills later in the summer, when the berm width reaches its maximum, the fill material, if placed in the subaerial portion of the profile, could remain longer before total redistribution. However, this situation minimizes the potential benefit taken from the nourishments operations during the bathing season in terms of an increase of the carrying capacity of the beach.

It becomes clear, therefore, that an integrated view accounting for benefits, costs and impacts not only from an environmental, but also from a social and economic perspective, is crucial and cannot be subdued, being the key to achieve sustainable solutions operated on a learning-by-doing, bottom-up, empowerment paradigm. As there are so few studies on the costs and benefits of ASN projects, uncertainties are largely unknown and the need for further research is great.

The socio-economic drives, nourishment scenarios (conjugating or not hard engineering structures), and impacts considered, as well as damages and losses valued are still incomplete. For example, costs of land losses due to an increase of coastal erosion, costs of forced migration due to permanent damages in the coastal system, potential gains (not only economics) of a healthy beach for coastal protection, locals, tourists and all the local businesses affected to it, and the impact of ASN projects in combination with other drivers on ecosystems have not been assessed yet at a national scale. Scientific studies encompassing analysis of vulnerability of coastal uses in relation to possible impacts by coupling the present day evolution and planned uses mapping with different nourishment scenarios should be developed as an attempt to create an interface between science and practice, while taking due account the needs of coastal engineers and managers.

While there is high agreement on the potential benefits that can be achieved with the implementation of ASN projects, there is to date little systematic review as well as limited evidence on why ASN projects are effective in a given context (and not in another), which also emphasizes the need for research to better understand this context. This context comprises not only the local morphological characteristics but also the forcing conditions (waves, water levels, winds, etc.) at the project site, which represent to the major forces that will shape the beach and determine both the short- and the long-term fate of the fill material.

Also, one of the potentialities typically associated to sand nourishment projects is the fact that an area is created and/or maintained without the cost of erosion of another. By the end of the project lifetime, when the fill material no longer exists in the boundaries of the project site (mostly due to the action of wave-driven alongshore transport gradients), beaches located immediately downdrift are expected to be filled with this material. These effects have been discussed by the scientific community, although they are still not well understood. For instance, for the case of Barra-Vagueira coastal stretch (the main case study presented in this dissertation), in which several nourishments have been analyzed, the velocity of the alongshore transportability could not be assessed, leaving questions regarding the time that fill material placed at the Barra takes to reach the downdrift Vagueira or Mira beaches, and that should be investigated in the future.

This dissertation has also focused on numerical approaches for simulating the response of a nourished profile towards a new equilibrium state, yielding to an improved version of the CS-model. Apart from the simplifications included in the model, so that longer time scales could be addressed, the model has also some shortcomings that could be overcome in further studies. The relevance of including offshore losses in the simulations (could act as a sink or source of sediments) has been mentioned. Also, if the berm is re-built at a higher crest elevation, an undesirable scarp may form as a response to the wave power. However, the berm slope is maintained constant during the calculations. The benefits of allowing for a change in the berm slope during the simulation should be further investigated. Also, another obvious refinement of the model would be to include some parameterization of the bar shape (so far regarded as a lump on the profile whereas bars have also troughs). Such refinement may involve a fixed shape (*e.g.* triangular) with specific height and length to characterize the bar.

Finally, due to its compatible temporal scale and robustness, the coupling of the CS-model with a shoreline evolution model would increase the model predictability of the beach-dune system response, as the gradients in longshore transport could be included through numerical inputs of shoreline change computations.

Considering all the previous points, the developed research contributes one step forward to the increase of knowledge regarding the performance of artificial sand nourishments, but it is equally recognized here a vast field of research that could be explored in the future.

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APPENDICES

PAPER I

Palalane, J., Fredriksson, C., **Marinho, B.**, Larson, M., Hanson, H., Coelho, C. **(2016)**; *Simulating Cross-shore Material Exchange at Decadal Scale. Model Application*. Coastal Engineering, Elsevier, 116, 29-41 pp. DOI: 10.1016/j.coastaleng.2016.05.007

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Simulating cross-shore material exchange at decadal scale. Model application

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ABSTRACT

A model developed to describe long-term cross-shore (CS) exchange of sand and resulting profile evolution at regional scale was employed to simulate the evolution at three different sites. The model consists of modules for calculating dune erosion and overwash, bar-berm material exchange, and dune build-up by wind-blown sand transport, as described in detail in a companion paper (Larson et al., 2016). Selected study sites represent coastal stretches influenced by beach nourishment (Barra in Portugal), overwash and breaching (Macaneta spit in Mozambique), and dune development (Ängelholm in Sweden). The model applications showed overall good performance and the results of the simulations are promising. Due to limitations in data availability in Ängelholm and Macaneta, values on calibration parameters were mainly determined based on previous studies. For Barra, where more field measurements were available, the application showed good agreement between the simulated results and observations. The CS-model proved to be a useful tool to predict long-term evolution of beach-dune systems in a time perspective from years to decades. However, additional efforts should be directed towards improving the schematized model profile so that it can better represent other beach shapes such as a sloping berm or a barrier shape.

1. Introduction

Beach erosion is threatening coastal societies, economical values, and valuable nature worldwide (Bird, 1985). The European project EUROSION concluded that 20% of the European coastline suffers from erosion and that the direct loss of land is a small problem compared to the flood risk associated with undermining of coastal dunes and other sea defenses (Doody et al., 2004). Sea level rise is expected to increase erosion rates and extend the problems to areas that are not yet affected (Leatherman et al., 2000). As development of coastal areas continues, population and economical values that are threatened by erosion are expected to increase significantly (Line et al., 2014).

Sustainable planning of coastal areas requires long-term predictions of beach-dune system evolution, since dunes often serve as flood defense for low-lying hinterlands and as a sediment reserve for the beach. For simulation of shoreline evolution at large temporal (decades) and spatial scales (kilometers) models based on the one-line theory, first introduced by Pelnard-Considere (1956), are typically used. Some examples are GENESIS (Hanson, 1988), Unibest CL+ by Deltares, and LITPACK by DHI. In the one-line theory, beach profiles are assumed to maintain an equilibrium shape. As a consequence, morphological cross-shore changes due to *e.g.* storm erosion, seasonal variations, and sea level rise are neglected.

Models for cross-shore sediment transport, on the other hand, are commonly focusing on short-term changes due to storm erosion (hours to days), *e.g.* SBEACH (Larson and Kraus, 1989) and XBEACH (Roelvink et al., 2009), or short to medium term (month to year) simulations like Unibest TC by Deltares. Aeolian processes are typically not included.

To simulate long-term evolution of beach-dune systems, a computationally efficient, semi-empirical model for cross-shore sediment transport (hereafter referred to as the CS model) has been developed. In a companion paper by Larson et al. (in review), the theoretical foundation of the model is described in detail together with validation of the included model components against field and wave tank data.

The CS model takes into account processes of dune erosion, overwash, dune build-up from wind, and berm-bar exchange. The longshore sediment transport gradient is here accounted for as a

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continuous source or sink; but may be coupled to simulations of changes in the shoreline position, *e.g.*, a one-line shoreline evolution model.

The main objective of this study is to evaluate model performance by applying the CS model to three sites with different characteristics and purpose of application. The study sites are located at Barra in Portugal, Macaneta spit in Mozambique, and Ängelholm beach in Sweden. At Barra the CS model is applied to simulate the effect of nourishments, at Macaneta overwash and breaching, and at Ängelholm dune development at different longshore sediment transport gradients. Study sites with variation in morphology, tidal regimes and wave climate were chosen to test the general applicability of the model.

2. Methodology

The methodology adopted for the implementation of the CS model comprises four different stages, specifically: (1) specification of initial morphological conditions; (2) assignment of values for input parameters and forcing; (3) specification of model parameters and calibration; and (4) model forecasting with output of sediment transport and morphological changes. The specifics of each stage are illustrated in Fig. 1, and developed in the following paragraphs. Adopted notation and corresponding units are summarized in a list of symbols exhibited at the end of the article.

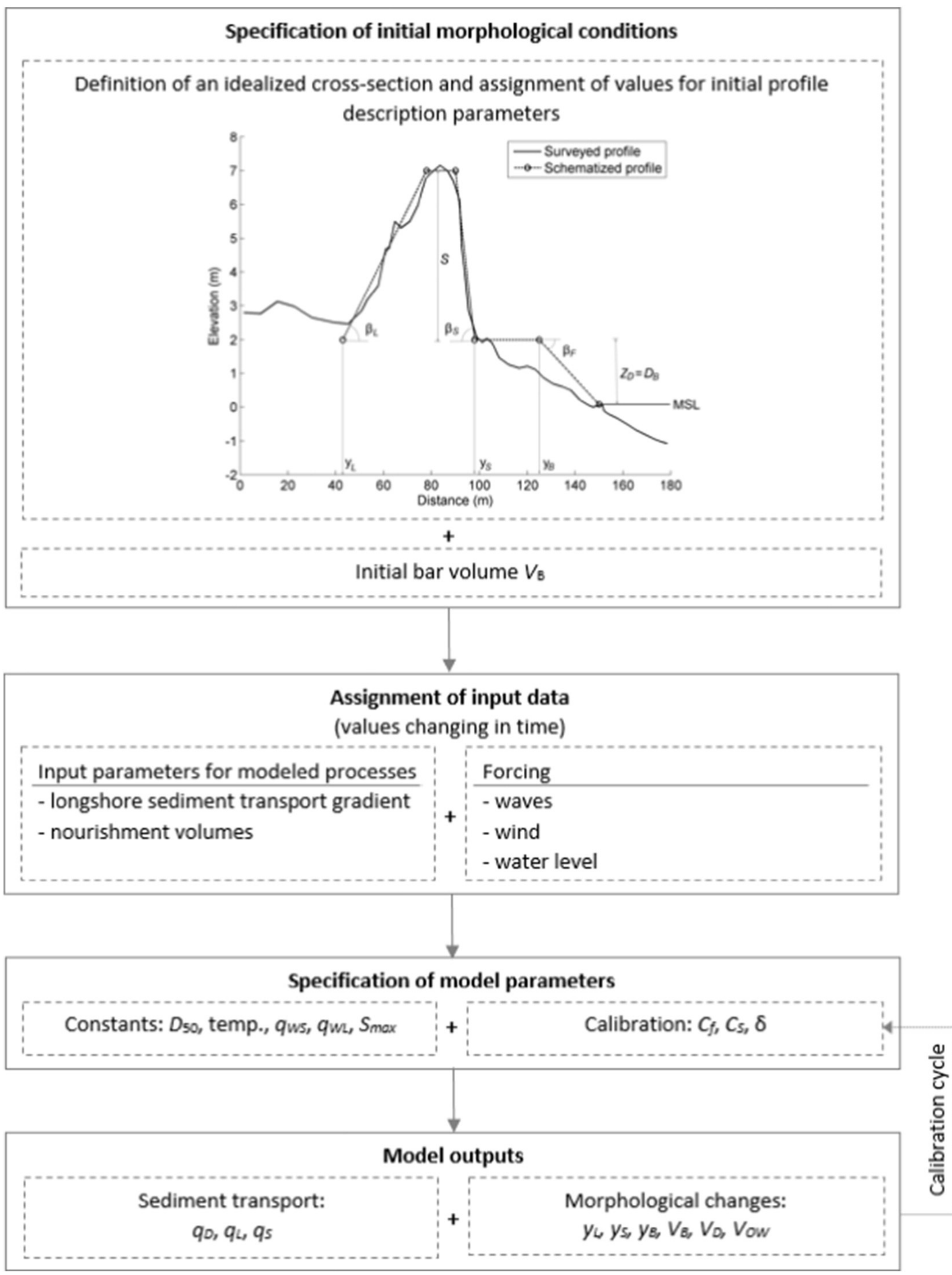

Fig. 1. Cross-shore model implementation stages.

The current model formulation considers an idealized CS profile with a berm. The berm width is given by the difference between the location of the berm crest (y_B) and the location of the seaward end of the dune (y_S). In the case where a berm is not present, a berm with a small width is considered. If the berm is sloping, the berm elevation D_B is set at the same level as the seaward dune foot elevation (Z_D), and y_B at half the berm width assuming a constant slope of the berm. With this procedure the berm volume is correctly represented.

The dune height is described by a variable, S, with a constant maximum value of S_{max}. If $S = Smax$, the dune shape is trapezoidal, and if $S < S_{max}$, it is triangular.

Wave heights were adjusted for oblique wave angles before employed in CS calculations using the formulation by Hanson and Larson (2008),

$$H_o^{'} = H_o\sqrt{cos\theta} \tag{1}$$

Where $H_o^{'}$ is the modified wave height used in the CS model calculations and θ is the offshore incident wave angle. Eq. (1) is used under the assumption that the runup height and the sediment exchange processes between the bar and the berm are related to the onshore component of the wave energy flux.

For the dune build-up by wind-blown sand, a constant or varying (wind speed dependent) transport rate can be adopted as described in the companion paper by Larson et al. (in review). In the absence of wind data, constant wind-blown transport towards the dune on the seaward side (q_{WS}) and constant wind-blown transport towards the dune on the landward side (q_{WL}) values are adopted. This option implies that the grain size is only used to calculate the fall velocity and not the rate of Aeolian transport.

Shoreline change due to longshore sediment transport was accounted for by adjusting y_B through adding or subtracting the corresponding accretion or erosion rate. Changes in shoreline position in reaction to beach nourishments were accounted for by adding the corresponding volumes to the bar or berm (depending on where sand was placed) during nourishment periods.

Model calibration was performed by adjusting site-specific input parameters and estimated input values based on previous studies. The performance of each specific run during the calibration exercise and validation exercises was analyzed quantitatively through comparison of the results with existing measurements of shoreline position (represented by y_B). Bar and dune volumes were estimated from surveys. When quantitative data were limited, the calibration and validation processes were performed by comparing results and trends of changes in beach profile evolution and volumes of beach features with documented information from reliable sources.

3. Application in Barra-Vagueira, Portugal

3.1. Background

Barra-Vagueira is a 10 km long coastal stretch, located in Aveiro district on the northwest coast of Portugal (Fig. 2). In this coastal stretch, the CS-model is applied to simulate cross-shore beach and dune evolution between 2009 and 2013. The purpose is to predict the medium-term response of a cross-shore profile due to the main forcing conditions (waves, water levels and winds), in order to assess the performance of beach nourishments as a measure to control beach erosion and protect adjacent urban areas.

The Barra-Vagueira coastal stretch is located between Espinho and Cabo Mondego, one of the most heavily eroding portions of the Portuguese coast. Its proximity to the Aveiro lagoon and urban areas, its low-lying sandy topography and a fragile dune system, being susceptible to overtopping and flooding due to severe wave conditions and significant tidal amplitudes, make this coastal stretch a very vulnerable and exposed area to erosion (Coelho et al., 2011; Pereira et al., 2013). As a result, there is an assumed imminent risk of breaching of the dune system that separates the Aveiro lagoon from the sea. This risk is aggravated by heavy erosion mainly caused by a deficit in sediment supply from rivers and sediment blockage by manmade structures. The 1.8 million m^3/year of sediment that under normal conditions would come from Douro River and feed the littoral drift towards south

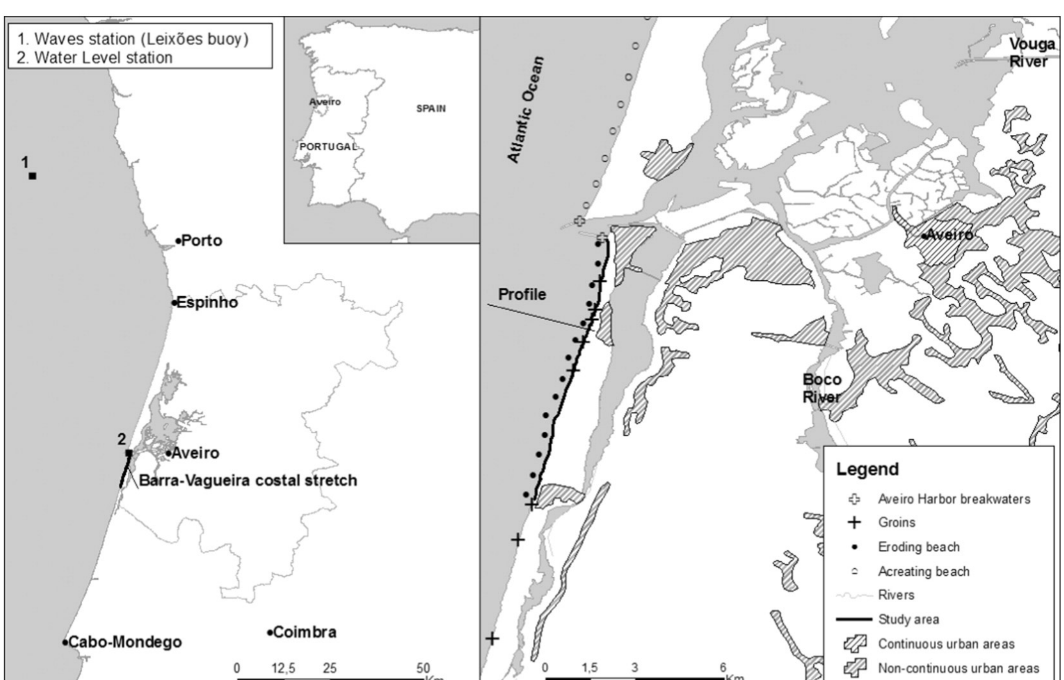

Fig. 2. Map of Barra-Vagueira costal stretch (right). Location of wave buoy and water level station (left).

(estimated to 1.5–2.0 million m^3/year), has been decreased to about 0.25 million m^3/year (Coelho, 2005; Coelho et al., 2009a, 2009b). As the longshore sediment transport is interrupted by the Aveiro Harbor breakwaters, an intense accumulation of sand occurs on the updrift (north) side and a significant retreat of the shoreline is occurring on the downdrift (south) side. This retreat is controlled by a groin field and a seawall along Costa Nova beach, and a seawall and a groin along Vagueira beach (Fig. 2).

The CS model was set up for one profile (Fig. 2), which is located close to the urban areas and considered representative for the studied coastal stretch.

3.2. Data

3.2.1. Waves

In general, the Portuguese west coast, which includes the coastal region of Aveiro, is heavily exposed to waves generated in the North Atlantic. The wave climate is essentially characterized by components of distant generation. These components have higher wave heights and longer periods than those that would be generated by action of the local wind. The mean significant wave height is around 2–3 m while the mean period is between 8 and 12 s. During storms, especially common in winters, offshore significant wave heights, coming predominantly from northwest, may reach 8 m, and persist for up to 5 days (Pires, 1989; Coelho, 2005; Coelho et al., 2009b).

The wave regime is obtained from data recorded at Leixões buoy, operated by the Portuguese Hydrographic Institute (IH). This buoy is located 78 km NNW from Aveiro, at a depth of 83 m (Fig. 2). Measurements from Leixões wave buoy is considered to be representative for the offshore wave conditions at the study site (IH, 2015).

Time series of peak period (T_p) and associated directions (θ), significant wave height (H_s), and average of the periods corresponding to H_s (T_{Hs}), with 3-hours intervals, were available for the period 2009–2013 (Fig. 3). During this period maximum and average significant wave height of 8.3 m and 2.0 m, respectively, were observed. The maximum wave peak period was around 18.4 s, with an average value of 9.2 s.

3.2.2. Water levels

Data on tidal projections, available from the Portuguese Hydrographic Institute (IH) for the Aveiro Harbor, were used to characterize

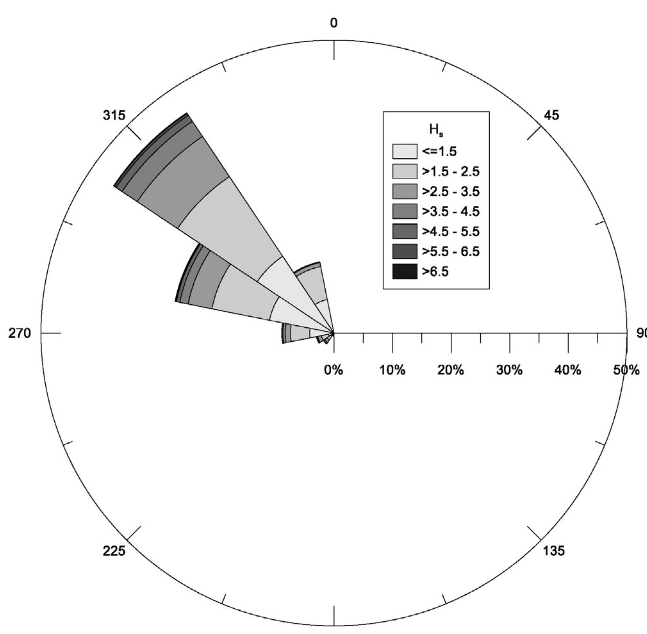

Fig. 3. Wave rose with energy based significant wave height, H$_s$, at Leixões (2009–2013).

the sea water level (SWL) between September 2009 and November 2013. The projections are calculated based on harmonic analysis of tide gauge observations of variable duration (IH, 2015). Based on projected high and low tide values a sinusoidal interpolation (Eq. 2) was employed to obtain the elevations of SWL, in relation to Chart Datum (CD), at the same time that wave records were collected.

$$z_t = \frac{H_t + h_t}{2} + \frac{H_t - h_t}{2} \cos \frac{\pi t}{T_t} \tag{2}$$

where, z_t is the sea water level at the moment after a high or low tide, t is the time interval between the previous extreme tide and the interpolation moment, H_t and $h_{t,}$ are the values of two consecutive extreme tidal projections (before and after the evaluated instant, respectively) and T_t the time period between them (IH, 2016).

Generically, the tide regime in Aveiro is semi-diurnal, with an amplitude range between 2 m during neap tides, and almost 4 m during spring tides (Coelho, 2005; Coelho et al., 2009b; Pereira and Coelho, 2013). Based on SWL data available, the mean tidal level is calculated in 2 m (in relation to CD), presenting an average tidal amplitude of 2.04 m and a spring amplitude of up to 3.46 m. The maximum value of high tide occurred on 2 March 2010 and reached 3.75 m.

3.2.3. Interventions

In order to control beach erosion along the Barra-Vagueira coastal stretch and improve the conditions of the Barra navigation channel, two major projects were undertaken by the Aveiro Harbor Administration (APA) between 2009 and 2013: “Dredging of Barra with reinforcement of the dune system” in 2009 and “Reconfiguration of Barra north breakwater” in 2012–2013. The main objective of the first project was the dredging of 1 million m^3 of sand (performed in two periods, see Table 1) from the bottom of the inlet entrance of the Aveiro Harbor and the use of the resulting sand to reinforce the littoral system in the Costa Nova beach. The second project conducted by APA was the extension of the north breakwater by 200 m, realignment of the channel and dredging works to ensure a bottom level of −12.5 m (CD).

The dredged material from the channel and breakwater extension was deposited in the subaqueous part of the beach profile in two main sites. The first site was bounded by the 3rd and the 5th groins of Costa Nova (counting from north to south, Fig. 2), at a depth between 2 and 5 m in 2009 and between 4 and 7 m water depth in 2012–2013. The second site in 2012–2013 was limited by the south breakwater and the 1st groin of Costa Nova beach (2012–2013), between 4 and 7 m water depth.

3.2.4. Sediments

According to the National Information System of Littoral Resources (SNIRL), Barra-Vagueira coast is composed of beaches with medium to coarse sands in its subaerial part and medium to fine sands in the subaqueous part.

In the absence of samples collected in the field to perform a sediment size analysis, a median sand grain size, $D_{50,}$ of 0.3 mm was specified. This value is consistent with the study developed by Narra

Table 1
Volumes, provenience and dates of dredging/deposition works (Porto de Aveiro, 2013).

Volume of dredged material (m^3)	Source of dredged material	Date of dredging/deposition
999,224 (50 + 50%)	Navigation	19/04/2009 to 15/05/2009; 20/09/2009 to 27/10/2009
169,218	Breakwater construction	13/06/2012 to 22/06/2012
66,725	Breakwater construction	05/2013
1,259,834	Navigation	28/06/2013 to 22/07/2013
97,724	Navigation	5/10/2013 to 18/10/2013
101,573	Navigation	11/2013

et al. (2015) which analyzed in total 165 sediment samples collected at 5 different points along 3 cross-shore profiles during 8 months, in Barra beach.

3.2.5. Morphology

Overall, the beach profiles possess a dominant seasonal variation and presents an intermediate to dissipative general morphodynamics north of the Aveiro Harbor breakwaters and intermediate morphodynamics south (SNIRL, 2015).

Topo-hydrographic surveys for 12 cross-shore profiles were collected between 20/09/2009 and 26/11/2013 by APA covering the study site. The profiles were surveyed from the top of the dune to a depth −10.0 m (CD) or deeper, and spaced 1 km each.

The profile with the highest data quality along the subaerial part of the beach and located closest to the urban areas was selected (Fig. 2). This profile, at Costa Nova beach, was also one of the profiles directly affected by both nourishments performed by APA. Fig. 4 displays the surveys collected for this profile, as well as the position of the landward and seaward dune foot and the seaward berm limit. The seaward dune foot location, y_S, was specified at the dune foot position of the profile where it registered the lowest horizontal variation along time between field surveys (5.9 m above MSL). According to the survey of 26/11/2013, which presents a very pronounced berm crest, the seaward berm limit, y_B, was specified at a location 4.1 m above MSL.

A short analysis of the topo-hydrographic surveys identified a positive sediment balance between September 2009 and November 2011, contributing to a total accretion of approximately 66 m^3/m. Between November 2011 and June 2013 about 307 m^3/m were eroded from the profile. Between June and November 2013 a significant accretion of about 902 m^3/m was verified mainly due to sand nourishment works performed in this period (see Table 1). The analysis is based on the part of the profile that is covered by all surveys. A pronounced submerged sand bar with a crest elevation at 3.5 m below MSL and volume of 266 m^3/m was also observed in 2010.

According to the long-term shoreline evolution study developed by Veloso-Gomes et al. (2006), for a period between 1980 and 1990, the shoreline retreat rate in Costa Nova beach is estimated to be 3.7 m/year. This rate was included in the CS-model as a constant retreat of the berm.

3.3. Model setup and calibration

The initial cross-shore profile was schematized according to the survey of 20/09/2009. The Aveiro beach profile type differs from the schematized model profile shape, as there is typically no horizontal berm (see Fig. 4). On the contrary, the berm can exhibit different slopes over time. In the calibration process, the berm width was defined approximately as half of the beach width. For this reason, the model results are compared with half the measured berm width. The initial morphologic characteristics of the profile are displayed in Table 2.

The model was calibrated with the measured profiles, following a parameters optimization process in order to obtain the best model results that reproduce the observed beach-dune system response. So, based on this procedure, the parameter C_S (coefficient in the dune impact formula) was set at 1×10^{-3}, which is within the interval 1.7×10^{-4}–1.4×10^{-3} presented by Larson et al. (2004) when validating the model with large wave tank and field data. Since the berm was defined as half beach width, after an iterative process of value optimization, the friction coefficient, C_f, was set to 0.01 as a way to reduce the front speed of the wave affected by the friction as it propagates towards the dune face. In the absence of wind data, the aeolian sediment transport was calibrated against the observed profile evolution to a constant rate of 4.6×10^{-7} m^3/s. The adopted values of q_{ws} and C_s parameters corresponded to a balance between the dune growth and wave impact that could represent the observed dune evolution. The δ coefficient was assumed equal to 0.1, being in the order of values proposed by Larson et al. (in review), and the water temperature was equal to 15 °C.

In 2009, no submerged bar was registered (see Fig. 4). However, an initial bar volume of 100 m^3/m was assumed for calibration of the CS-model. This volume represents not only the bar volume but also all nearshore deposits. The effect of the beach fills was introduced during the simulation considering individual additions of sediment to the bar volume, due to its proximity to the deposition area (see Fig. 4, survey from 26/11/2013). The sand added was specified based on the ratio of the nourished areas.

A depth of closure, D_C, equal to 12.4 m was calculated using Hallermeier's (1981) formula. This value is in agreement with D_C–values usually considered for the Aveiro coast, which are between 12–15 m (Coelho, 2005), and within the observed limit of the vertical variation of the profile (see Fig. 4).

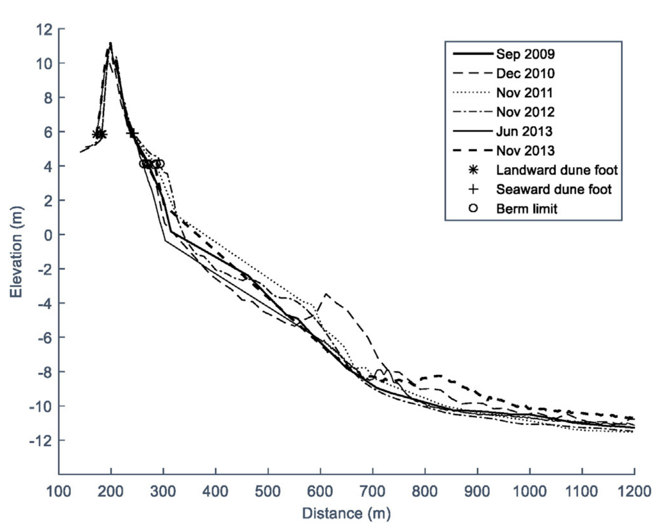

Fig. 4. Topo-bathymetric surveys of profile, between 2009 and 2013 (elevation relative to mean sea level).

3.4. Results

In general, the cross-shore model results show good agreement with the observed profile evolution (Figs. 5 and 6).

The bar volume increases during the winter months due to more energetic wave conditions. Significant decreases in dune volume and berm width are observed at the beginning of each winter, when the first storms hit the dune and move large amounts of sediment, feeding the bar. At the end of summer the profile is restored. Sediment has been transported back to the beach from the bar during less energetic wave conditions and wind transport has rebuilt the dunes. These seasonal variations are well represented in the model results.

The major beach nourishment volumes added to the bar volume, V_B, can be identified as instantaneous increases (in October 2009 and July 2013). However, the rapid increase that can be observed in 15–26 January 2010 does not result from fill operations. The beach was subject to frequent wave attack with run-up levels exceeding the dune foot, Z_D. After this event, the simulated minimum dune volume was observed as well as the highest bar volume (491 m^3/m). The dune foot, y_S, retreated by 2.5 m, and the berm width, y_S-y_B, decreased by 7 m. This

Table 2
Morphological parameters, initial values of variables.

y_L (m)	y_S (m)	y_B (m)	S (m)	S_{max} (m)	D_B (m)	V_B (m^3)	β_L (−)	β_S (−)	β_F (−)
181	240	255	5	5	5.9	100	0.30	0.14	0.07

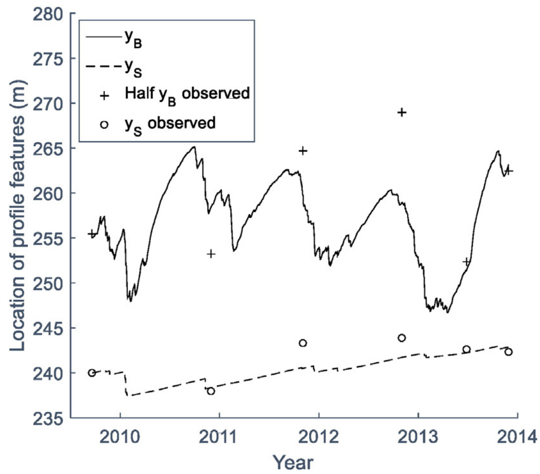

Fig. 5. Result profile: calculated y_S and y_B; observed y_S and y_B.

extreme event may be the cause of critical damages to the dune structure only registered by the topo-hydrographic survey of December 2010, evidencing a significant decrease of the dune volume and height in relation to the other surveys.

The simulated seaward dune foot position, y_S, follows the evolution trend of the observed position. The maximum deviations registered between computed and observed values are about 2.8 m and 2.2 m, in November 2011 and November 2012, respectively (Fig. 5). The berm evolution simulation indicates a slower recovery process compared to the retreat that occurs during storms. The simulated berm width (y_B-y_S) and berm position (y_B) trends follow the observed gains and losses of sediment, with an average deviation from the measured values of about 2.6 m and 3.7 m, respectively. In 2010, 2011 and 2012 the observed berm deviates significantly from the simulated values, reaching a maximum difference of about 10 m in November 2012. These deviations may result from that the observed berm values were collected at the beginning of winter periods, and that the meteorological effects on the water levels are being neglected. Considering this, the first impacts of the storms might have induced additional dune erosion, increasing the sand transport to the berm, and further increasing the beach width.

The simulated dune volume shows an increasing trend with time (Fig. 6) which is in line with observations. However, dune erosion due to the storm in October/November 2010 is underestimated in the model as the observed dune volume is 24 m^3/m lower than the

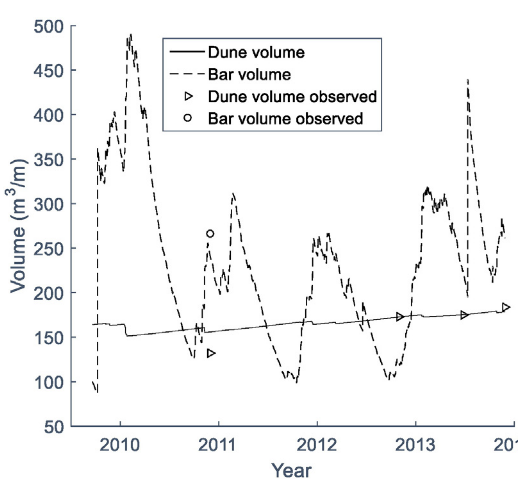

Fig. 6. Result profile: calculated dune and bar volume; observed dune and bar volume.

simulated, resulting in the maximum deviation registered during the simulation period. As previously mentioned, the meteorological effects not considered in the SWL data may be inducing this behavior. As discussed before, the topo-hydrographic survey carried out in December 2010 confirms that critical damages to the dune structure happened before. The average deviation between simulated and measured values of V_D is 8 m^3/m.

The topographic surveys only show the presence of a bar after the storm in October/November 2010. The model results indicate that the profile surveys are performed at times when the bar volume is close to its minimum value. In December 2010, the simulated bar volume was approximately 27 m^3/m lower than the observed (Fig. 6). At the same time, the model overestimated the observed dune volume suggesting that the impact of the storm is not accurately reproduced by the model.

The profiles that show higher retreat rates (November 2013, December 2010, and September 2009) are the same in the model results and in the topo-hydrographic surveys.

4. Application in Macaneta spit, Mozambique

4.1. Background

Macaneta is a 12-km long sandy spit located in southern Mozambique, just north of Maputo City and Maputo Bay. The spit has two isthmus which appear as weak sections at which breaching might occur, if extreme waves and subsequent erosional events happen. Thus, the CS model was applied to model cross-shore sediment transport along the Macaneta spit. The purpose was to simulate the CS spit evolution during the last 18 years, based on hindcasted historical waves and water level fluctuations. Focus was also put on the identification of critical scenarios during which the occurrence of dune erosion, overwash, and breaching can threaten the spit integrity at selected critical sections.

The spit has a north–south development with the Incomati river estuary along its west bank and the Indian Ocean along its east bank. The spit width varies from 80 m at the most critical isthmus section to around 640 m at the widest spit section. Dunes are present along almost all the spit formation. In the northern part of the spit, around twenty summer houses can be identified. Some temporary and temporary fishing camps can also be found along all the stretch of this recreational beach.

4.2. Data

To model the evolution of the beach-dune system during an 18-year simulation period, two profiles representing the most critical sections of the spit where chosen (sections A and B; see Fig. 7). As previously mentioned, only cross-shore sediment transport was analyzed as the longshore sediment transport gradient was found to be small (DHI, 2013).

4.2.1. Waves

Hindcasted time series of significant wave, peak period, and peak direction from the Wave Watch III model (NOAA/NCEP, 2013) was used to characterize the wave climate along the spit. First, offshore wave data were extracted for a point located nearly 80 km seaward of the spit, with latitude 26 °S and longitude 33.5 °E. The extracted dataset was 18 years long. It gave values for the three main wave characteristics from February 1997 to March 2015, at 3 hours interval.

The offshore wave data were propagated to the nearshore area adjacent to the spit using a modified version of the EBED model (Nam et al., 2009). Nearshore waves were extracted for two points in line with two studied sections at depths of 12 m and 8 m (for sections A and B respectively). The points were both located 6 km off from the spit, but downdrift of Dannae shoal, a submerged sand formation which

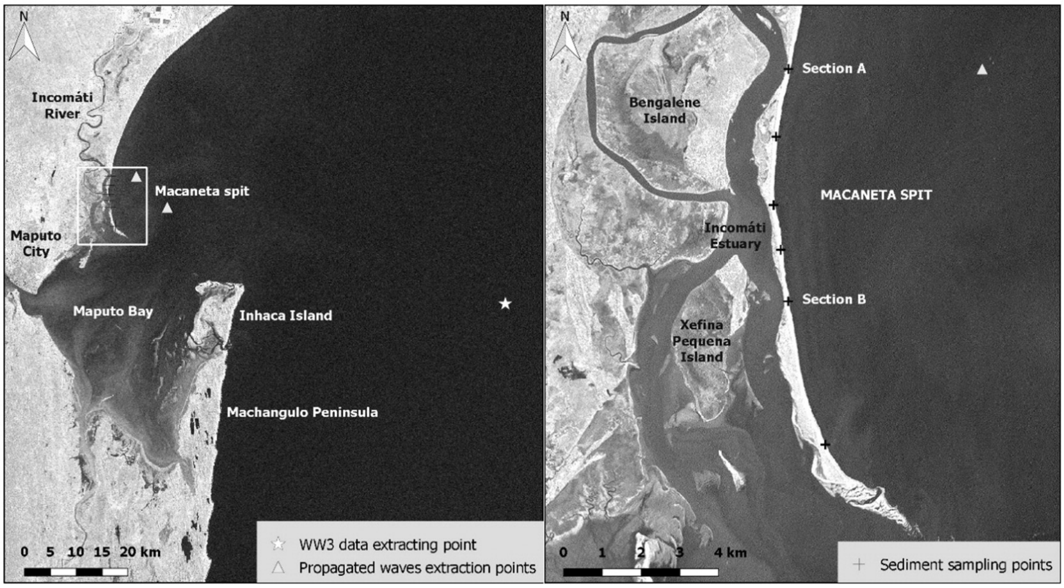

Fig. 7. Location of the study site and main interest features (modified after USGS/NASA Landsat).

provides some sheltering of the spit, especially for higher waves. Propagated waves reached the extraction points with maximum and average significant wave heights of 3.2 m and 0.95 m off of section A, and 3.3 m and 0.85 m off of section B (Fig. 8). The maximum wave peak period was around 18 s, with an average value of 6.6 s in both sections.

4.2.2. Water levels

Fluctuations in the mean water level due to tidal variations were accounted for in the model. The MatLab Tidal Fitting Toolbox (Grinsted, 2008) was used to fit tidal components to a time-series of modeled variations in sea level due to astronomical tides from DHI (2013). This dataset consisted of sea level values from February 2005 to February 2013, with one-hour time step. It was fitted to tide components using the least-squares method with a relative residual of 0.037. The fitted model was later employed to generate a time-series for the entire simulation period, from February 1997 to March 2015. Tide values ranged from −1.41 m to +1.41 m. Obtained results were in agreement with values presented by de Boer et al. (2000) and Karlsson and Liljedahl (2015), the last extracted from WXTide (Hopper, 2007).

4.2.3. Sediments

A field survey was conducted between March 17 and 19, 2015, during which sediment samples were collected for six different sections of the spit (Fig. 7) at the foredune, berm, swash zone, and breaker zone. The results did not show any clear trend of increase or decrease in diameter from north to south or *vice-versa*. Comparing the medium diameters from different beach features, coarser D_{50} values were found at the swash zone, between 1.10 and 1.11 mm for sections A and B, respectively. These values decreased both seaward and landward, following the pattern observed by Narra et al. (2015). Thus, landward, D_{50} varied between 0.29 and 0.62 mm at the foredune, and was found to be equal to 0.72 and 0.70 mm at the berm, for sections A and B, respectively. Seaward, the D_{50} was equal to 0.34 and 0.30 mm at the breaker zone.

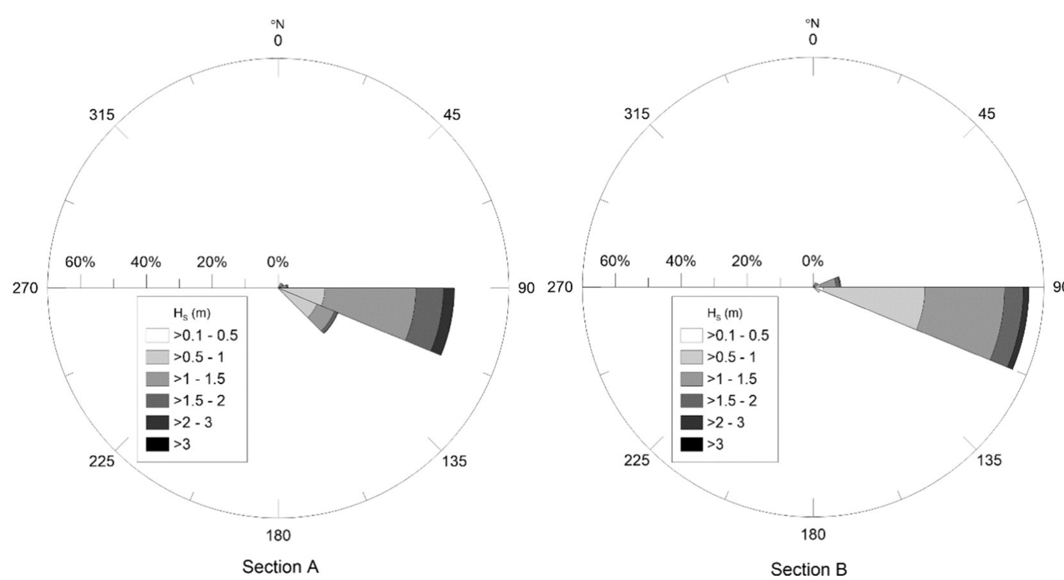

Fig. 8. Propagated wave climate 6 km offshore of Macaneta spit critical sections.

Following the suggestion by Narra et al. (2015) that the upper foreshore limit at high tide is the best sampling point for a representative D_{50} for the profile, which tends to correspond to the berm edge, a value of 0.66 mm should be adopted to represent the average of D_{50} values from the berm. However, as a constant wind-blown sand transport rate was considered, D_{50} will only be used to compute the setting velocity and the equilibrium bar value. Thus, D_{50} values at the breaker zone around 0.30 mm (as indicated above) were adopted.

4.2.4. Morphology

Observations of different maps and aerial photos suggest that the gradient in the longshore transport is small. Therefore, the most significant changes in the beach profile are linked to cross-shore processes (Sayo et al., 1994; DHI, 2013; Karlsson and Liljedahl, 2015). In line with this assumption, DHI (2013) and Karlsson and Liljedahl (2015), based on comparison of the location of the vegetation line from aerial photos, have found that the isthmus at section A has been stable during the last two decades on its seaward side. A comparison of a rectified old aerial photo dated from August 1989 and a Google Earth image from 2011 suggested that if erosion is occurring, its rate should be no more than 0.1 m/yr in the northern part of the spit (DHI, 2013). This study suggests that the main reason for this low erosion rate and the stability of the spit is the fact that the shoreline orientation is almost equal its equilibrium value for the incoming waves. However, Karlsson and Liljedahl (2015) indicated that the isthmus at section B is migrating eastwards as the vegetation line migrated around 20 m eastwards on its seaward side between 2003 and 2014.

The north–south spit development suggests that its growth was most likely governed by a longshore transport directed southwards (see Fig. 7). However, at recent years, it has not experienced any noticeable growth. The results of numerical simulations conducted by DHI (2013) and Karlsson and Liljedahl (2015) found a predominant northward directed littoral drift. This pattern changes to a southward net longshore transport at the northern part of the spit where section A is located.

Three profiles from December 8, 1993 were available for the northern stretch, where the most critical section A is located, but without any specific reference to the sea level (Sayo et al., 1994). The profiles extended from the riverward side of the dune to around 1 m water depth at the sea side. These profiles indicate that vegetated dunes with a height between 1.4 and 3.1 m existed at that time (Fig. 9).

During the March 2015 field campaign, cross-shore profiles and the position of the shoreline were measured with RTK-GPS. Surveyed profiles indicated a dune height of 1.2 m and 1.9 m, for section A and B, respectively. The berm width was 4.9 m at section B, whereas it was difficult to discern this beach feature at section A (Fig. 9).

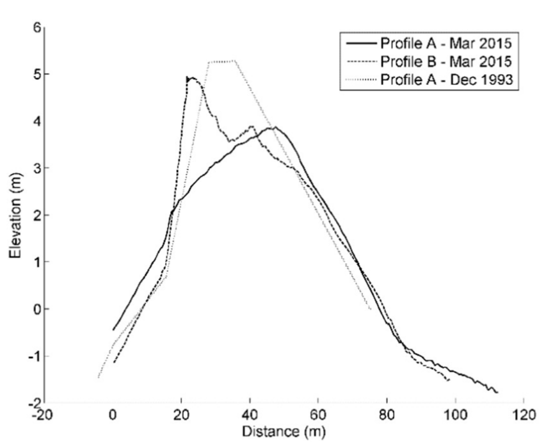

Fig. 9. Surveyed profiles at section A and B (elevation relative to mean sea level).

4.3. Model setup and calibration

The model was applied to simulate cross-shore sediment transport for nearly 18 years, between February 1, 1997 and March 31, 2015. The initial profile for section A was schematized based on the cross-section from December 1993 presented by Sayo et al. (1994), and on the surveyed profile from March 2015 available from Karlsson and Liljedahl (2015). Therefore, the initial location of profile features for February 1997 was obtained through a linear interpolation of the values available from these two surveys illustrated in Fig. 9. The initial dune height (S) was set equal to S_{max} as the interpolated value was high, differing substantially from the one given by the 2015 profile, and was not yielding good results. An average bar volume (V_B) from previous runs of the model was adopted as the initial value. A small berm with a width of 3.0 m was considered to exist at cross-section A, although both profiles from December 1993 and March 2015 show that it does not have a pronounced berm (Fig. 9).

For cross-section B, in the absence of historical surveys, initial values for the location of main profile features from the March 2015 survey were adopted, under the assumption that the dune and bar volumes, and the berm width fluctuates around an average value. It was also observed that even if starting with different initial values for variables for the length coordinates (y_L, y_S and y_B), after a year of simulation the dune and bar volumes, and the berm width converge to closer values dictated by the incident wave climate, sea level fluctuations, and wind-blown sand transport. Initial values for S and V_B were assigned using the same procedure as adopted for cross-section A.

All initial values for variables for length coordinates, dune and berm heights, and bar volume are presented in Table 3. Input values of constants used to describe the morphology, constant dune slope angles (β_L and β_S), foreshore slope angle (β_F), and maximum dune height (S_{max}) are also presented in Table 3. Another constant input value is the depth of closure, D_C, which was calculated using Hallermeier's (1981) formula, and considered uniform and equal to 6.0 m (Karlsson and Liljedahl, 2015).

For model site specific parameters, D_{50} was set to 0.34 and 0.30 mm, corresponding to the medium diameter found at the breaking zone, were adopted for cross-sections A and B, respectively. Water temperature was specified to be 22 °C. Standard values from previous studies which involved field work and laboratory experiments were adopted for site parameters and coefficients which were not possible to obtain from undertaken field work at Macaneta.

The model calibration was performed by changing the wind-blown sand transport rate, q_{WS}, the coefficient expressing the spatial growth of wind transport rate, δ, the impact formula transport rate coefficient C_s, and the coefficient for frictional losses over the berm C_f, so that the overall behavior of changes in the spit profile and almost stable shoreline position reported for cross-section A, and an eastward migration of the spit at cross-section B could be reproduced. In line with the above, the condition of an almost stable shoreline position was considered to occur if the position of the berm crest (y_B) fluctuates around a mean value. The achievement of this condition was assessed by comparing how close to a horizontal line will the linear fitting of y_B be. For cross-section B, the simulated position of the seaward dune foot (y_S) was compared with four measurements of the location of the vegetation line (y_{veg}) available from Karlsson and Liljedahl (2015), for June 2003, January 2007, September 2010, and August 2014. The position y_S was chosen to be compared with y_{veg} as it was noted for Macaneta that the

Table 3
Morphological parameters, initial values of variables.

Profile	y_L (m)	y_S (m)	y_B (m)	S (m)	S_{max} (m)	D_B (m)	V_B (m^3/m)	β_L (−)	β_S (−)	β_F (−)
A	22.1	53.0	56.0	1.4	1.4	3.0	70	0.057	0.190	0.144
B	19.0	48.5	53.4	1.9	1.9	3.0	65	0.633	0.081	0.113

vegetation line starts between the seaward dune foot and the dune crest, being frequently closer to the former. To account for this eastward migration of the spit at section B, an advance shoreline rate of 2.3 m/yr was assigned to y_B, to represent a gradient in the longshore sediment transport.

Best results were obtained for C_S set equal to 1×10^{-4}, being inside the range of values for the impact formula transport rate coefficient suggested by Larson et al. (2004). In the absence of good wind data, a constant wind-blown sand transport rate, q_{WS}, at equilibrium conditions, of 9.2×10^{-7} m^3/s/m was considered. A coefficient expressing the spatial growth of wind transport rate $\delta = 0.2$ was adopted. The coefficient for frictional losses over the berm was calibrated to $C_f = 0.02$.

4.4. Results

The cross-shore sediment transport was successfully computed for the 18-years simulation period, as the indication of a stable shoreline could be represented for cross-section A, and the pattern of eastward migration for cross-section B. The stable shoreline is indicated by an almost horizontal $y_{B,fit}$ line visible from Fig. 10, which during the 18-years simulation period had a low eastward migration of 1.4 m in section A. For cross-section B, the eastwards migration rate of the spit given by measured $y_{veg,fit}$ and simulated $y_{S,fit}$ were equal to 1.82 m/yr and 1.74 m/yr, respectively (Fig. 11). Thus, it was possible to reproduce the eastward dune migration, occurring at a lower rate than the assigned shoreline advance rate (represented by y_B) of 2.3 m/yr. When comparing the four measurements of y_{veg} with the simulated y_S values for the same times, it can be seen that the simulated y_S lays in front of y_{veg} in June 2003 and August 2014, being the minimum distance between these two features of 1.03 m observed in the latter. On the other hand, simulated y_S lays behind of y_{veg} for intermediate times, January 2007 and September 2010, being the minimum distance between these two features of 2.61 m observed in the former.

The analysis of results focused on evaluating changes on beach profiles. These changes were represented by corresponding movements in time of the berm toe (y_B), positions of the dune foot landward (y_L) and seaward (y_S), illustrated in Figs. 10 and 11. In addition to that, the exchange of sediment between the dune and the bar was also analyzed. Changes in time of the dune and bar volumes are illustrated in Figs. 12 and 13. These figures also gives an additional indication (+ signs) of periods during which overwash events were observed.

Figs. 10 and 11 illustrate how the combined action of incoming waves and wind-blown sand is contributing to alternate between periods of gains and losses of sediment, which therefore govern the berm width, and dune width and volume. It is also possible to notice from Fig. 10 that the seaward location of the berm crest is oscillating around an equilibrium value at cross-section A. A similar behavior of

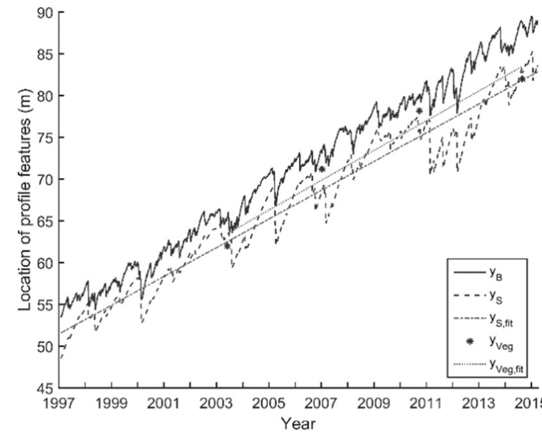

Fig. 11. Result profile B: calculated y_S, y_B, measured y_{Veg}, and linear fittings for y_S and y_{Veg}.

oscillating around an equilibrium value is exhibited by the location of the seaward dune foot for the first 13 years of the simulation although the deviations from the equilibrium are bigger. These behavior agrees with the finding that the shoreline is not experiencing a significant retreat at cross-section A although cycles of accretion and erosion are occurring, as suggested by DHI (2013) and Karlsson and Liljedahl (2015). The same oscillation pattern around a mean value is equally valid for y_B and y_S at cross-section B, although with a positive increasing trend which substantiates the reported migration of the spit towards the sea.

The occurrence of extreme events can be linked to the passage of tropical storms or cyclones hitting the Mozambican coast. This is clearly illustrated by Figs. 10 to 13 which indicate the most severe erosion event affecting simultaneously sections A and B, observed in March 2012. During this erosion event, the lowest simulated dune volumes equal to 9.8 m^3/m and 12.4 m^3/m were observed at sections A and B, respectively, as well as the maximum bar volumes equal to 125.3 m^3/m and 124.9 m^3/m. This resulted in one of the highest retreats observed in less than a week in both sections (Figs. 10 and 11). These extreme values are linked with the Severe Tropical Storm Irina which hit Macaneta during the first two weeks of March 2012. Although not reaching cyclone level this was the closest storm to the Macaneta spit during the entire simulation period, with wind speed velocities reaching 90 km/h on the 11th of March.

Larson et al. (2009) established a criterion which specifies that breaching is considered to occur when 90% of the dune volume has eroded away. The largest dune erosion episodes due to the Severe Tropical Storm Irina did not satisfy the breaching criteria at both sections A and B. It should be mentioned that the model does not include a

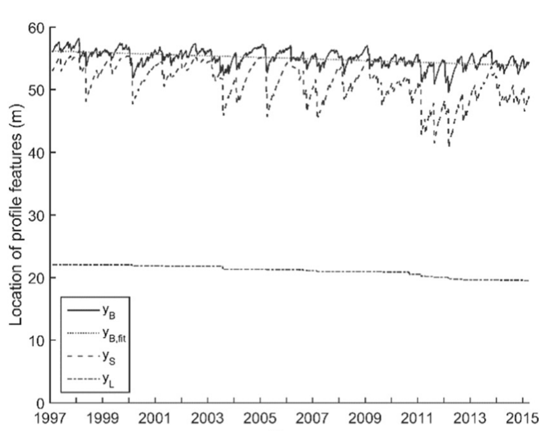

Fig. 10. Result profile A: calculated y_S, y_B, y_L and linear fitting for y_B.

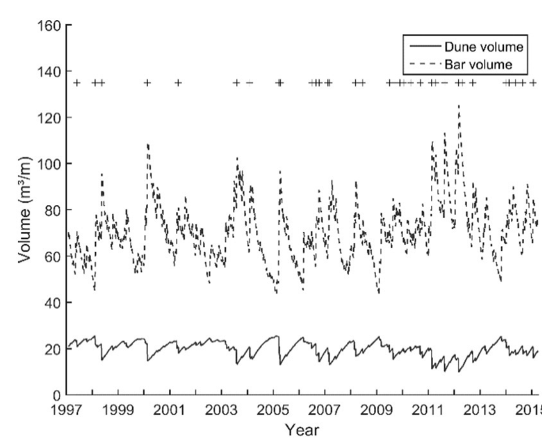

Fig. 12. Overwash events (marked with + signs), dune and bar volume changes with time at cross-section A.

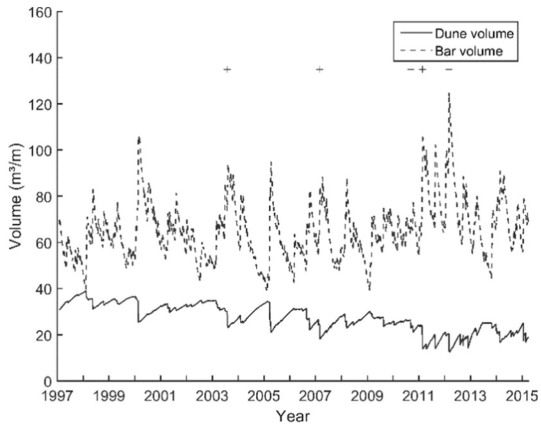

Fig. 13. Overwash events (marked with + signs), dune and bar volume changes with time at cross-section B.

formulation to account for sediment mobilization and transport by the river. Therefore, the dune keeps growing towards the river reducing the likelihood of breaching at cross-section A (see y_L changes from Fig. 10). On the other hand, it presents a decreasing trend at cross-section B (see Fig. 13) as a recession rate higher than the computed accreting rate y_S was assigned to y_L to represent the eastward migration of y_L. This eastward migration of y_L was described to be occurring at a higher rate than y_S by Karlsson and Liljedahl (2015).

Figs. 12 and 13 illustrate the interrelation between the emerged and immersed portions of the beach. This is illustrated by the fact that decreases in dune volumes are followed by increases in bar volume, and *vice-versa*. This joint variation pattern is explained by the fact that part of the sediment eroded from the dune feeds the berm, at the same time there is a transfer of sediment between the berm and the bar.

Figs. 12 and 13 also indicate that 84 overwash events were observed during the 18-years simulation period at section A, and 9 events at section B. The total overwashed volumes during the all simulation period were 3.1 m^3/m and 0.3 m^3/m for sections A and B, respectively. This significant higher value of overwash observed at section A can also be noticed when analyzing the locations of the riverward position of the dune toe (y_L) in Fig. 10.

5. Application in Ängelholm, Sweden

5.1. Background

Ängelholm beach is located in Skälderviken bay in the south of Sweden (Fig. 14). The CS-model was applied to predict shoreline and dune evolution in a 20 year perspective with the purpose to determine the necessary beach nourishment volume to ensure flood safety and mitigate erosion.

The beach is located between two rivers, Vege River in the south and Rönne River in the north with piers along the outlet (Fig. 14). The beach is sandy with a wide dune landscape which has partly forested during the 18th century to prevent aeolian sand transport to the nearby villages and arable land (Aurell, 1986). In the north part of the beach, the dunes are developed with houses and the hinterland consists of residential areas and a camping. Further south, the dune landscape and the hinterland are undeveloped (Fig. 14).

There is a positive sediment transport gradient from north to south, leading to erosion in the north part of the beach, and accretion and spit formation in the south part. The dunes are eroded during storms almost every year. In the south, where the beach is accreting, storm damages on dunes are observed to recover by natural processes. In the north, where the beach is eroding and dunes serve as flood protection for the low-lying hinterland, the recovery rate is too low and the seaward dune foot is gradually retreating.

To investigate the evolution of the beach-dune system on a decadal scale, the CS model was set up for three different profiles which represent eroding, accreting and stable sections of the beach. The alongshore sediment transport gradient was included in the model as a constant change of the berm volume.

5.2. Data

5.2.1. Waves

The wave climate was hindcasted from wind measurements at station Hallands Väderö (indicated as number 1 in Fig. 14), operated by the Swedish Meteorological and Hydrological Institute (SMHI). Hourly values of 10 min averaged wind speed and wind direction are available from 01/08/1995 until today.

Energy based significant wave height and spectral peak period were calculated at the bay opening using the CERC-formulations for wave hindcasting in deep and shallow water (USACE, 1984). The formulations were modified with a memory function, as used by Hanson and Larson (2008), so that existing wave conditions were remembered in the consecutive time step and wave growth and decay included.

The hindcasted wave series from 1995–2014 has maximum and average significant wave heights of 5.3 m and 0.51 m, respectively (Fig. 15). The maximum wave peak period is around 9.2 s, with an average value of 9.1 s.

5.2.2. Water levels

Water levels were collected from the SMHI station Viken (number 3 in Fig. 14). The SMHI station Ängelholm (number 2 in Fig. 14) is closer to

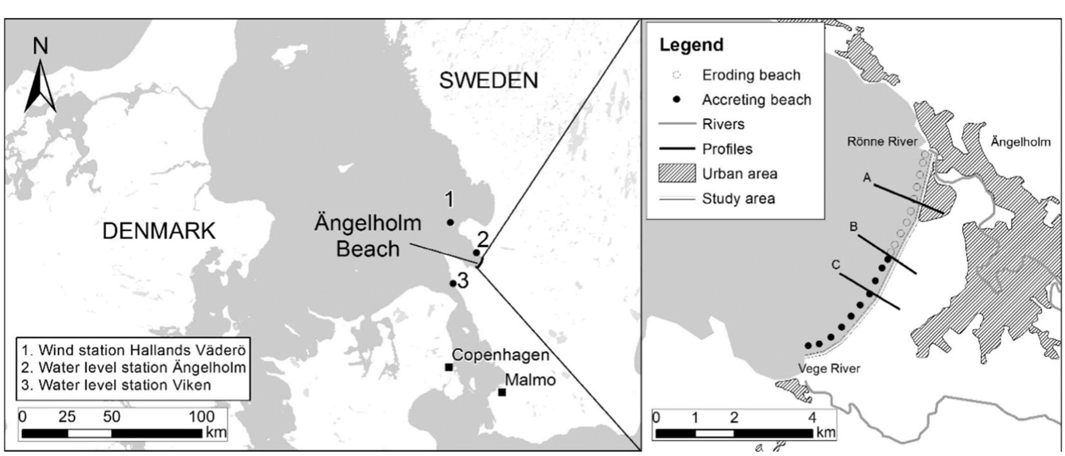

Fig. 14. Location of the study site and the wind and water level observations (left). Detailed map of the study site (right).

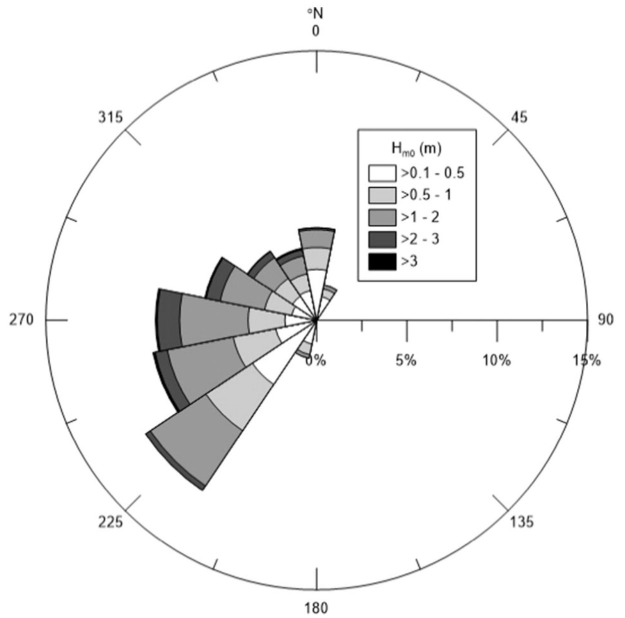

Fig. 15. Wave rose with energy based significant wave height, H_{m0}, at the Skälderviken bay opening.

the model area but has several gaps in the data series and has only been in use between 22/03/2011 and 07/05/2014.

During onshore winds, the water level at the study area is higher than at the SMHI-station in Viken, due to local wind setup in the bay. Assuming a rectangular shaped bay, negligible bottom friction and stationary conditions, wind setup, Δh, was calculated according to (USACE, 1984),

$$\Delta h = \frac{\rho_{air}}{\rho_{water}} \frac{C_D W_X^2 L_B}{gd} \tag{2}$$

where ρ_{water} is water density, ρ_{air} air density, C_D drag coefficient, W_x onshore wind speed component, L_B bay length, g gravitational constant and d average depth.

The drag coefficient, C_D, was determined to 2.3×10^{-3} by fitting Eq. (2) to the observed difference between water level in Ängelholm and Viken during onshore winds. There is large scatter in the data and the correlation coefficient is $r^2 = 0.17$ which indicates a complex relationship between the water level at the two stations. In a literature study, Kraus and Larson (1991) found that values of C_D normally are in the range of 1×10^{-3} to 3×10^{-3} and that large scatter in data sets are common.

Water level data from Viken was adjusted for wind setup calculated according to Eq 2. Wind set-down due to offshore winds was neglected since no waves are generated during those conditions that could affect the model results.

The tide in Kattegatt is semidiurnal with an average amplitude of about 5 cm and a spring tide amplitude of up to 20 cm. The characteristic water levels with recurrence interval of 2, 10, 25, 50 and 100 years are calculated for Viken (Table 4; SMHI, 2013).

In the study area, characteristic water levels may be up to 40 cm higher than in Viken due to wind setup during a 100-year storm (SMHI, 2013). During the simulated period, 1995–2014, the maximum water lever including calculated wind setup is 185 cm above mean sea level (MSL) in 27/11/2011 which corresponds to an event with a recurrence interval of 50–100 years.

Table 4
Characteristic water levels for Viken (SMHI, 2013).

Recurrence interval (years)	2	10	25	50	100
Water level (cm, rel. MSL)	111	142	156	165	175
95% confidence interval	104–119	132–161	143–185	149–205	155–228

5.2.3. Sediments

The median grain size (D_{50}) is varying along the beach from coarser (0.55 mm) in the north where the beach is eroding, to finer (0.19 mm) in the south close to the Vege River mouth (Sweco, 2011b). Studies have observed the grain size to decrease both seaward and shoreward from the swash zone (see *e.g.* Narra et al., 2015). Narra et al. (2015) concluded that the upper foreshore limit at high tide is the best sampling point for a representative D_{50} for the profile.

For profiles A, B, and C (for locations, see Fig. 14) sediment samples from the upper foreshore limit was collected 12/10/2015. D_{50} was determined by sieving to be equal to 0.29 mm (Profile A), 0.15 mm (Profile B), and 0.11 mm (Profile C).

In the CS-model, D_{50} is used to calculate fall velocity, so the representative grain size was assumed to be finer than in the swash zone samples. For profiles A, B, and C a representative D_{50} was estimated to 0.2 mm. However, the profile specific grain size at the upper foreshore limit is considered when determining aeolian transport rates.

5.2.4. Morphology

The municipality has surveyed 17 profiles in 26/11/2014 and 22/01/2015 with RTK-GPS (accuracy of 2 cm). The profiles stretch from the landward side of the dune to 1 m water depth. Profiles A, B, and C (Fig. 14) are chosen to represent, respectively, eroding, stable and accreting sections of the beach. The dune foot is located at +2 m (RH 2000) and the dune height is +6 m (RH 2000) in Profile A and B, and +3 m (RH 2000) in Profile C (Fig. 16).

The profiles were measured just before and after a storm causing moderate dune erosion. Dune erosion was estimated as the volumetric difference measured from the dune foot to the dune crest between the two surveys. The eroded volume from 26/11/2014 to 22/01/2015 was calculated to be 13 m^3/m in profile A, 1 m^3/m in profile B, and 3 m^3/m in profile C.

In 2011 and 2013 severe storms hit the beach and dune erosion was documented with field inspections and photos. After the storm 27/11/2011, the dune foot retreat was estimated to 3–5 m for profile A, about 3 m for profile B, and 1–2 m for profile C (Sweco, 2011a). After the storm in 5–6/12/2013 the damages were more severe. The dune foot retreat was estimated to 5–10 m for profiles A, B and C (WSP, 2013).

For this study, no detailed bathymetry has been available, only nautical charts, so there is no information about the subaqueous morphology. It is, thus, uncertain if bars are developed during storms or if sediment is transported to other nearshore underwater deposits.

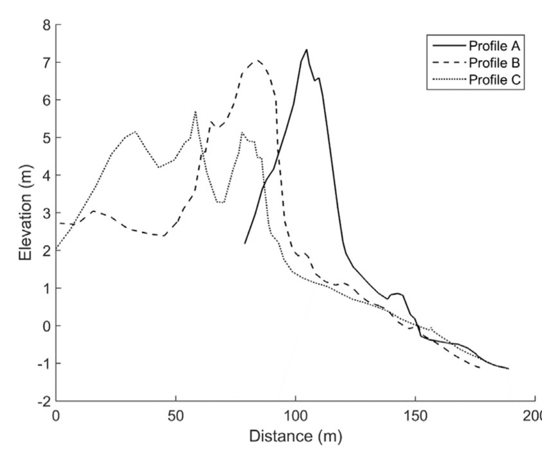

Fig. 16. Profile A, B and C intersecting at mean sea level, surveyed 26/11/2014 (elevation relative to mean sea level).

The depth of closure, D_C, was estimated to about 5 m based on the method presented by Hallermeier (1981). Wave heights used in the calculation were adjusted for oblique angles according to Eq. (1).

Long-term shoreline evolution was estimated with a GIS-tool, Digital Shoreline Analysis System (DSAS) (Thieler et al., 2009). The analysis was based on orthophotos from year 1940, 1947, 1963, 2000, 2007, 2010, 2012 and 2014 with varying coverage of the study area. Photos from 2012, 2014 and the 1940s (1940 or 1947) cover the entire beach.

The seaward vegetation line was defined in each photo and changes measured in shore normal transects with 50 m spacing. The rate of change was estimated by weighted linear regression, giving higher weight to photos with less uncertainty. Uncertainty of the shoreline position was conservatively estimated to +/− 10 m for the older aerial photos (from 1940, 1947 and 1963) and +/− 5 m for the newer. The uncertainty was estimated considering errors in orthophoto resolution and rectification, relation of the shoreline and the vegetation line and seasonal variability. The average weighted standard error for the entire stretch of the beach is 0.73 m/year.

The average yearly shoreline change is presented in Fig. 17. The standard error is large compared to the calculated changes, but the result is in line with previous observations of eroding and accreting stretches of the beach (Aurell, 1986; Sweco, 2011b).

North, updrift of the piers (0–125 m), the shoreline is advancing with 0.4–0.6 m/yearly. Along the Rönne River, immediately downdrift of the piers (125–1000 m), the beach is retreating with 0–0.2 m yearly. Further south, in the area around profile A (1000–2500 m), the erosion rate is higher, 0.2–0.4 m. At profile B (3350 m), the shoreline is stable over time and around profile C (4000–5500 m) the vegetation line is advancing seaward by 0.2–0.4 m/years. Close to the Vege River mouth (6500–6700 m) the shoreline is retreating but simultaneously a spit is growing towards SW indicating a net transport from north to south also here. The spit growth is estimated to approximately 500 m from the 1940's until today.

Profiles A, B, and C were chosen to represent parts of the beach that are eroding (−0.3 m/year), stable +/−0 m/year), and accreting (+0.3 m/year), respectively.

5.2.5. Interventions

The analysis of aerial photos indicated a positive gradient in the longshore sediment transport from north to south. As a consequence, sand is trapped on the north side of the piers at the Rönne River mouth and the beach is eroding on the south side. In year 2000, 53,000 m^3 sand was bypassed from north to south of the piers. The bypassed sand was placed north of the modeled profiles and not directly within any of them.

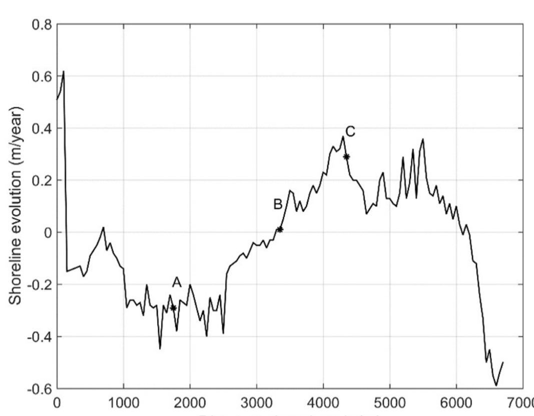

Fig. 17. Average yearly change of shoreline position (m/year) from 1940s until today. Distance along the beach is given in meters from the northernmost point of the study area. The position of the modeled cross-sections is indicated by asterisks and letters.

In the south where the beach is accreting, dunes recover after storms and prograde seaward. In the north, where the beach is eroding, the dune growth rate does not keep up with the rate of storm erosion. After the two most severe, recent storms (27/11/2011 and 5–6/12/2013), sand has been moved by excavator from the foreshore to increase the dunes' resistance against future storms. The sand was moved within the profile so that the dune volume increased while the volume in the subaqueous profile decreased. In April 2012 and April 2014, 14 m^3/m and 28 m^3/m of sediment, respectively, were added to the dune in profile A, but none in profiles B and C.

5.3. Model setup and calibration

The profiles were schematized based on the profiles measured in 26/11/2014 (Fig. 16). The beach does not have a pronounced berm and the slope is rather constant from the dune foot to 1 m depth. The input berm width was therefore defined as half the beach width.

The landward position of the dune foot was set at 10 m from a reference point for each profile. The initial positions for the seaward dune foot, y_S, and the berm crest, y_B, were adjusted to account for the observed erosion/accretion trend from 01/08/1995 until 26/11/2014 by adding 0.3 m/year to profile A and subtracting 0.3 m/year from profile C. The initial variables for length coordinates (y_L, y_S and y_B), maximal dune height (S_{max}), berm height (D_B), bar volume (V_B) and constant dune slope angles (β_L and β_S) are presented in Table 5.

The depth of closure (D_C) was set to 5 m and the representative median grain size, D_{50}, was estimated to 0.2 mm. Water temperature was set to 15 °C.

The shoreline change corresponds to −0.3 m/year and 0.3 m/year for profiles A and C, respectively, as observed in the DSAS-analysis. The sand volume that was used to replenish the dune in profile A, was added as a volume to the dune and subtracted as a volume from the bar. The volumes were 14 m^3/m in April 2012 and 28 m^3/m in April 2014, respectively.

The period between the profile measurements in 26/11/2014 and 22/01/2015 were used to calibrate parameters related to storm impact − C_S, C_f, and initial bar volume. The calibrated value of the impact coefficient, $C_S = 8 \times 10^{-4}$, is within the range of values, 1.7×10^{-4}–1.4×10^{-3}, found by Larson et al. (2004) when validating the impact model against large wave tank data and field data. The friction coefficient, C_f, was calibrated to 0.02 which is the same as employed in the model setup at Westhampton beach, Long Island, New York (Hanson et al., 2010).

The coefficient expressing spatial growth of wind transport rate, δ, was set to 0.1 according to the result of calibration against field data in Larson et al. (in review). The potential aeolian transport rate, q_{WS}, was calibrated so that the observed long-term trend (from the DSAS-analysis) in the evolution of the vegetation line is reproduced, to 3.15×10^{-7} m^3/s/m (Profile A), 3.3×10^{-7} m^3/s/m (Profile B), and 3.4×10^{-7} m^3/s/m (Profile C). The difference in potential sediment transport rate is supported by the variation of median grain size, D_{50}, among the profiles. Wind climate being equal, a profile with finer D_{50} is assumed to have more sediment available for aeolian transport and thus a higher potential transport rate. The calibrated constant wind transport, q_{WS}, amounts to 10–11 m^3/year/m. De Vries et al. (2012) studied dune evolution along the Holland coast in Netherlands and found an upper limit of measured dune growth of 30 m^3/m/year. The

Table 5
Morphological parameters, initial values of variables.

Profile	y_L (m)	y_S (m)	y_B (m)	S (m)	S_{max} (m)	D_B (m)	V_B (m^3/m)	β_L (−)	β_S (−)	β_F (−)
A	10	57	72	5	5	2	30	0.21	0.50	0.014
B	10	65	92	5	5	2	30	0.14	0.63	0.015
C	10	88	116	3	3	2	30	0.11	0.27	0.016

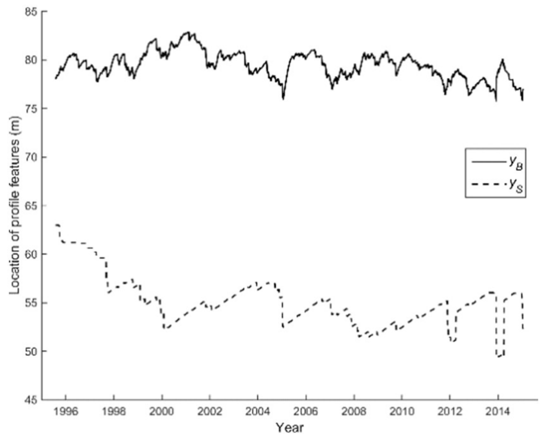

Fig. 18. Result profile A: calculated y_S and y_B.

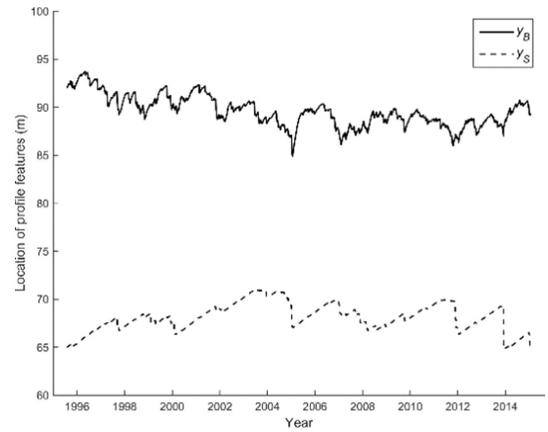

Fig. 20. Result profile B: calculated y_S and y_B.

beaches along the Holland coast are wider, with higher dunes, are exposed to stronger winds, and are nourished. Considering these differences larger aeolian transport would be expected along the Holland coast than in Ängelholm. The calibrated wind transport value for Ängelholm is, therefore, considered to be within a reasonable range.

5.4. Results

The model was run for a period of 19.5 years from 01/08/1995 to 22/01/2015. The results — in terms of the locations of the seaward dune foot, y_S, and the berm crest, y_B, are presented in Figs. 18, 20 and 22. During the simulation period there is no change in position of the landward dune foot, y_L, in any of the profiles, therefore it is not included in the figures. The calculated volumes in the dune and the bar are presented in Figs. 19, 21 and 23.

Profile A is starting with a narrow berm which is rapidly growing in the beginning of the simulation, due to dune erosion. The input profile is based on profile measurements after sand was moved to the dunes, thus the starting profile is not in equilibrium and the dune width is expanding on behalf of the berm width. Profiles B and C, on the contrary, show decreasing berm width as sediment is blown in to the dunes. To better represent the actual behavior of y_B and y_S, respectively, the calibration needs to be improved for the different profiles and for that, more data for calibration and validation is needed, *e.g. in situ* measurements of wind-blown sediment transport and additional profile measurements.

There is a strong signal in the results from storms in 2004, 2011 and 2013. The damages in 2011 and 2013 were documented by visual inspections (Sweco, 2011a; WSP, 2013) and compared with the result of simulations (Table 6).

The inventory of the erosion was carried out when the slope of the dunes were very steep, just after the storms. In the CS-model, dune slope angles were fixed for an average slope that is milder than dune slopes after storms, thus the simulated retreat of the dune foot may be less than the observed for the same eroded volume which may explain why the model result is somewhat lower in the result from 2013. Another factor is the uncertainty of local water level during the storm, underestimation of wind setup would result in underestimation of dune erosion. The comparison of model results with observations after the storms in 2011 and 2013 validate that the model results are in the correct order of magnitude.

6. Discussion

The model applications at the three different study sites show an overall good performance. In the case of Macaneta and Ängelholm, field data for calibration and validation were scarce, and more measurements are required to better calibrate model specific parameters and validate model performance. However, the calibration parameters were within the same range as determined in previous studies, and the few observations of profile evolution were reasonably well reproduced. The CS-model exhibited robust behavior during the simulation periods, which were 18 and 19.5 years long. The application in Barra, where more field measurements were available, showed overall good agreement between the simulated results and observations.

Fig. 19. Result profile A: calculated dune and bar volume.

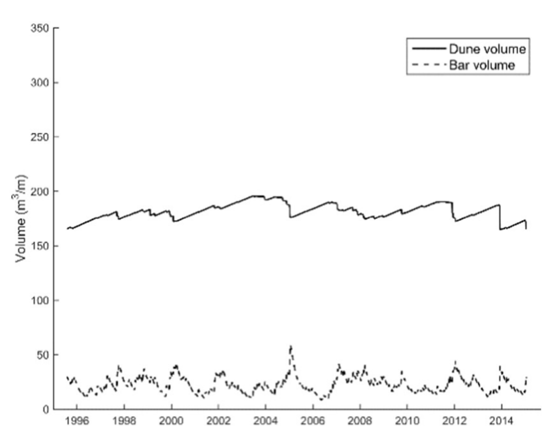

Fig. 21. Result profile B: calculated dune and bar volume.

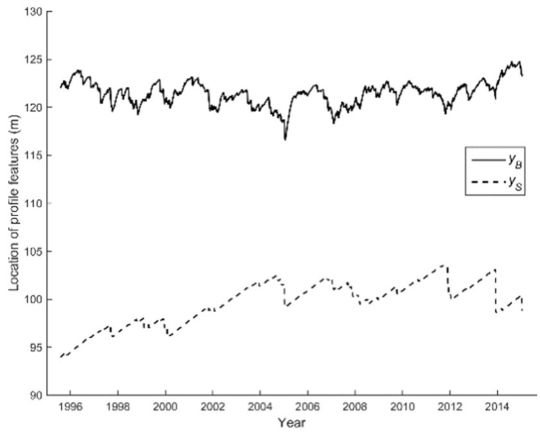

Fig. 22. Result profile C: calculated y_S and y_B.

Water level during storms is an important input parameter to the model as it affects the runup level. The eroded dune volume is proportional to the square of the runup height exceeding the dune foot, R-Z_D. In Ängelholm, the water level data series from Skälderviken bay is too short and there is large scatter when calibrating the wind setup with a station outside the bay. For the case of Macaneta and Barra, only water level data for astronomical tide was available and the meteorological contribution was not considered. For calibration of the dune erosion impact coefficient, C_S, site specific water level data and morphological observations are important. The calibrated impact coefficients were ranging from 1×10^{-4} to 1×10^{-3}, all within the range found by Larson et al. (2004).

In these applications, aeolian transport was considered as a constant potential rate which was calibrated to 4.6×10^{-7} for Barra, 3.15×10^{-7}–3.4×10^{-7} for Ängelholm and 9.2×10^{-7} m^3/m/s (corresponding to 29 m^3/m/yr) for Macaneta. The potential rate at Macaneta is between two and three times larger than at the other sites. This rate is below the total wind-blown transport of 53 m^3/m/yr estimated for Westhampton Beach, Long Island by Hsu (1994) cited in CEM (2008). However, sediment supply rate can be considered high when comparing with maximum computed dune volumes at Macaneta which was equal to 35 m^3/m/yr during all simulation period. The coefficient expressing the spatial growth of wind transport rate, δ, is set to 0.2 for Macaneta and 0.1 for the two other sites which would further increase the difference in transport rates as a smaller coefficient implies a larger effect of the berm width. However, the berm at Macaneta is narrow which in effect means that the potential rate will not be reached at all times. For a berm width of 4.5 m, 50% of the potential transport is reached and for a berm width of 10 m, 90%. Further study of the mechanism behind aeolian transport at the different study sites, *e.g.* wind climate and grain size, are needed in order to further discuss this difference.

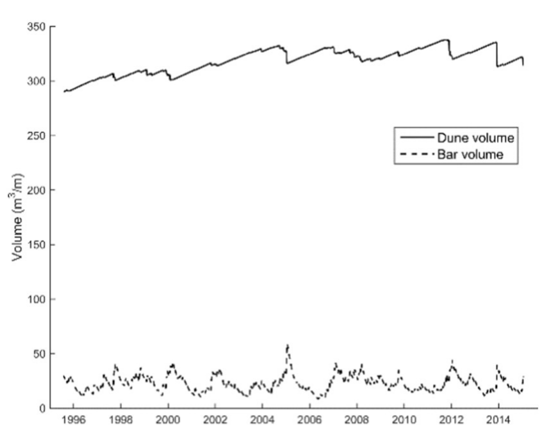

Fig. 23. Result profile C: calculated dune and bar volume.

Table 6
Observed and simulated retreat of seaward dune foot, y_S, after storms in 2011 and 2013.

Profile	2011, observed retreat y_S	2011, simulated retreat y_S	2013, observed retreat y_S	2013, simulated retreat y_S
A	3–5 m	4.3 m	5–10 m	6.5 m
B	3 m	3.4 m	5–10 m	4.5 m
C	1–2 m	3.6 m	5–10 m	4.5 m

Of the three study sites, subaqueous profile measurements were only available for Barra. Among six profile measurements, there was only one where a clearly defined bar was visible. In Ängelholm, it is uncertain whether bars are present. Analyses of aerial photos indicate that sediment after storms is transported to other forms of nearshore deposits. The purpose of calculating the berm-bar exchange is to simulate the varying berm width. The bar volume can be considered as a representative volume of storage in the bar but also in other nearshore deposits from which sediment is exchanged with the berm.

The CS-model is based on a schematized profile which is not optimal for all beach types. In Macaneta, the most critical profile has no berm and in Ängelholm and Barra, the berm is sloping and not horizontal as in the model schematization. In Macaneta, a minimum berm width of 3.0 m was applied to the profile without a berm. In Ängelholm and Barra, the profiles were adjusted by assuming that the berm corresponds to half the beach width and that the berm elevation is equal to the seaward dune foot elevation. In this way, considering a constantly sloping berm, the berm volume is correctly represented, but the berm width is only half that of the real profile which may imply underestimation of runup friction and aeolian transport. This error can be compensated by calibration of the friction coefficient, C_f, and the aeolian transport rate coefficient, δ, relating the aeolian transport to the berm width. In this study the friction coefficient, C_f, was varying between 0.01–0.02 and the aeolian transport rate coefficient, δ, between 0.1–0.2. To improve the physical description, the schematized model could be developed to better represent other beach shapes such as a sloping berm or barrier shape.

For applications at spits where the landward side of the dune is facing the river, sediment transport gradients in the river should be included as a sink or source in the model to better represent the evolution of the landward side of the dune.

7. Conclusion

The CS-model was successfully applied to simulate cross-shore evolution at three sites, Ängelholm, Barra and Macaneta. One of the strengths of this model lies in the simplified schematized cross-section to represent the beach profile. The adoption of a simplified representative profile allows short simulation times while keeping the model stability.

The main limitations faced during the implementation of the CS-model were imposed by lack of data from Ängelholm and Macaneta. Thus, model specific parameters were calibrated based on limited quantitative data available, and qualitative/descriptive information available from documented reliable sources. This was not the case of Barra, where it was possible to successfully calibrate and validate the model since more measurements were available.

The model application at these three different sites pointed out that improvements of the modeling capabilities should be directed to introduce more versatile cross-sections which can better represent sloping or the absence of berms.

The results of the simulations look promising and the CS-model has proved to be a useful tool to predict long-term evolution of beach-dune systems which is important to estimate risk of dune breaching or overtopping in a time perspective from years to decades. Its robustness, reliability, and relatively short calculation times imply a high potential for CS model to be included in a general long-term coastal evolution model.

List of symbols

Parameter	Description	Unit
C_S	Impact formula empirical transport rate coefficient	–
C_f	Coefficient for frictional losses over the berm	–
C_D	Drag coefficient	–
D_B	Berm crest height	m
D_C	Depth of closure	m
D_{50}	Median sediment diameter	mm
d	Average water depth	m
g	Gravitational constant	m/s^2
H_o	Deep water wave height	m
H'	Modified wave height for run-up calculations	m
H_s	Significant wave height	m
L_B	Bay length	m
q_D	Cross-shore transport rate	m^3/s/m
q_L	Overwash transport	m^3/s/m
q_S	Seaward transport resulting from erosion of the dune (backwash transport)	m^3/s/m
q_{WE}	Equilibrium sand transport rate by wind	m^3/s/m
q_{WL}	Constant wind-blown transport on the shoreward side	m^3/s/m
q_{WS}	Constant wind-blown transport towards the dune	m^3/s/m
R	Wave runup height	m
S	Dune height	m
S_{max}	Max dune height	m
T_p	Wave peak period	s
T_{Hs}	Wave period corresponding to H_s	s
Tt	Tide period	s
t	Time	s
V_B	Bar volume	m^3/m
V_D	Dune volume	m^3/m
V_{ow}	Overwash volume	m^3/m
W_x	Onshore wind speed component	m/s
y_B	Location of berm crest (represents the shoreline position)	m
y_L	Location of landward end of the dune/barrier	m
y_S	Location of seaward end of the dune/barrier (dune foot)	m
Z_D	Vertical distance from the mean water level to the dune foot	m
Z_t	Water level	m
$ß_F$	Foreshore slope	–
$ß_L$	Landward slope of the dune/barrier	–
$ß_S$	Seaward slope of the dune/barrier	–
Δh	Wind setup	m
Δ	Coefficient expressing the spatial growth of wind transport rate	–
ρ_{water}	Water density	kg/m^3
ρ_{air}	Air density	kg/m^3
θ	Offshore wave incident angle	°

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.coastaleng.2016.05.007.

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PAPER II

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Short- and long-term responses of nourishments: Barra-Vagueira coastal stretch, Portugal

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Abstract Dredged material resulting from deepening and maintenance activities of the Aveiro Harbor inlet channel, northwestern coast of Portugal, has been used to mitigate the erosion trend recorded on nearby beaches (from Barra to Costa Nova Beach) through direct placement of sand by using standard dredge equipment. The disposal activities of dredged material have been undertaken at two main sites: between the south breakwater and the 1st groin of Costa Nova (dumping area 1, DA1) and between the 3rd and the 5th groin of Costa Nova (dumping area 2, DA2).The sand was placed in the nearshore, between the −2 and −7 m Chart Datum, CD, contours.

In this study, short- and long-term coastal morphologic changes in the sea bottom, in response to several nourishment operations and to the incoming waves, within the dumping area boundaries are investigated based on a data set of hydrographic surveys collected annually, just before and after the nourishments, between 2009 and 2015. Preliminary results describing the main morphologic changes, evolution trends, sediment budget variations, and nourishments performance are discussed using mainly Geographic Information System techniques. Overall, the analysis demonstrates that the short-term losses in the dumping areas (one month of interval) can reach 50% of the nourished volume, revealing a significant movement of the fill material towards offshore. Seasonal variations promoting cross-shore material exchange can also prevail and misrepresent the sediment balances, if the monitoring area is not comprehensive. Furthermore, some bathymetric analysis suggested that longshore transport gradients have moved the fill material from Barra beach to downdrift areas. All the obtained results contribute to the ongoing discussion about the effectiveness of nearshore sand placements especially in context of an energetic environment.

Keywords Dredging · Artificial nourishment · Morphodynamic · GIS · Monitoring

Introduction

With the increasing urban pressure over the coastal areas, economic growth, sea level rise and recurrent storm-induced beach erosion events, a demand for adaptive coastal management strategies, able not only to provide coastal protection but also create areas for nature and recreation, has been intensely encouraged during the latest decade. In this respect, sand nourishments are typically considered as a soft coastal protection strategy since its pure concept does not involve the construction of hard-structures. This type of solution is becoming popular between coastal engineers and managers due to the several benefits that they can offer (not only environmental but also socials) to mitigate erosion, ensure flood safety and increase beach width. Recently, as a way to explore the positive attributes from such projects, several innovative coastal maintenance approaches have been emerging. An international example is the well-known pilot

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project "Sand Engine" (completed in 2011). Based on a mega-nourishment approach, this project was designed to assess the effectiveness of concentrated fills (in time and space) on protecting the Dutch coast (Schipper *et al.*, 2016). Although large steps have being given in attempting to maximize the potential benefits taken from beach nourishments, their behavior is still poorly understood, the control over the sand nourished is minimal and questions about the ultimate fate of the nourished sand are still unanswered (Di Risio *et al.*, 2010; Jacobsen and Fredsoe, 2014).

Typically, sand nourishment projects focus on the subaerial portion of the beach morphology by reconstructing specific coastal features as the dune and beach berm. However, when using sediments from dredging, for practical and economic reasons, nourish on the subaerial beach becomes less attractive than in the subaqueous portion since dual underwater operations may be realized at considerably less time and cost, minimizing the movement and the number of equipment required for fill placement (Gravens *et al.*, 2003). Several issues related to the suitability of an underwater approach to the fill placement for coastline preservation still require investigation, especially in view of the strong demand for reducing beach fill maintenance costs.

There are different strategies for nearshore sand placement, including profile nourishment (where sediments are placed along the active cross-section in order to approximate the equilibrium shape) and the placement of sand as an artificial offshore bar (where sand is placed to form a reservoir promoting beach growth and wave energy dissipation along time). Here, the latter technique will be investigated. Although external material placed nearshore becomes part of the beach system, benefits to the beach have not been well quantified (Larson *et al.*, 2015). Database consisting on results of nearshore berm projects needs to be disseminated. Particular data of interest include wave data and bathymetric surveying data. In this respect, anticipated follow-up programs play an important role since they focus on field data acquisition campaigns as a way to objectively assess and measure the impact of the project. However, monitoring is in many cases neglected and seen as a concern of second order, reason why very few field data sets are available to support research projects.

In Portugal, artificial beach nourishments have been applied as coastal protection measure in some beaches of Algarve, in Costa da Caparica and Castelo do Queijo (Coelho et al. 2011a). Although monitoring results available for major projects have been discussed by the coastal community, very few monitoring data are well comprehensive in time and space, once large amounts of funding are required. In Aveiro, recent artificial beach nourishments have been carried out along Barra-Vagueira coastal stretch. Sediments coming mostly from deepening and maintenance activities of the Aveiro Harbor navigation channel have been placed into the beach system through nearshore deposits as a way to control the shoreline recession. As a result, Aveiro Harbor Administration initiated in 2009 a monitoring program that have been developed since then in order to register the main morphologic beach changes within the dumping areas.

Here, based on a data set of hydrographic surveys collected annually, just before and after the nourishments, short- and long-term responses to the nourished sand placed in the dumping areas are investigated over six years approximately (2009–2015). The aim is to characterize the morphodynamic behavior and the mobility of the nourished material on Barra and Costa Nova beaches.

The present paper is organized as follows. In section 2, a brief presentation of the study area is given, describing its physical setting, the main coastal interventions undertaken (dates, volumes, locations, etc.) and the field observations. The methodology is outlined in section 3 and the morphological evolution of the fills by focusing on sea bottom adjustment within the nourished areas in connection to the incoming waves is analyzed in section 4. Discussions are given in section 5 and the main conclusions are summarized in section 6.

Field site characterization

Barra-Vagueira is a 10 km long coastal stretch, located in Aveiro district, on the northwest coast of Portugal (Figure 1). This stretch, approximately centered on the sandy coastal stretch between Espinho and Cabo-Mondego, is currently subjected to structural erosion (corresponding to a generalized deficit of sediments). Its proximity to the Aveiro lagoon and the urban areas, as well as its low-lying sandy topography and fragile dune system, susceptible to overtopping and flooding during high-energy events, makes this coastal stretch a very vulnerable and exposed area to erosion (Coelho et al. 2011b; Pereira et al. 2013). Due to the severe wave conditions and large tidal amplitudes easily achieved during the winter (storm situations), this area is also threatened by an imminent risk of breaching of the dune system that separates the Aveiro lagoon from the sea. This risk is aggravated by heavy erosion mainly caused by a deficit in sediment supply from rivers and sediment blockage by manmade structures. The 1.8 million m^3/year of sediment that under normal conditions would come from Douro River and feed the littoral drift towards south (estimated to be 1.5–2.0 million m^3/year), has been decreased to about 0.25 million m^3/year (Coelho 2005; Coelho et al. 2009a, 2009b; Costa and Coelho 2013; Palalane et al. 2016).

At the study site, the beach profile type possesses a dominant seasonal variation and presents an intermediate to dissipative general morphodynamic in the north of the Aveiro Harbor breakwaters and an intermediate morphodynamic at south (SNIRL, 2015).

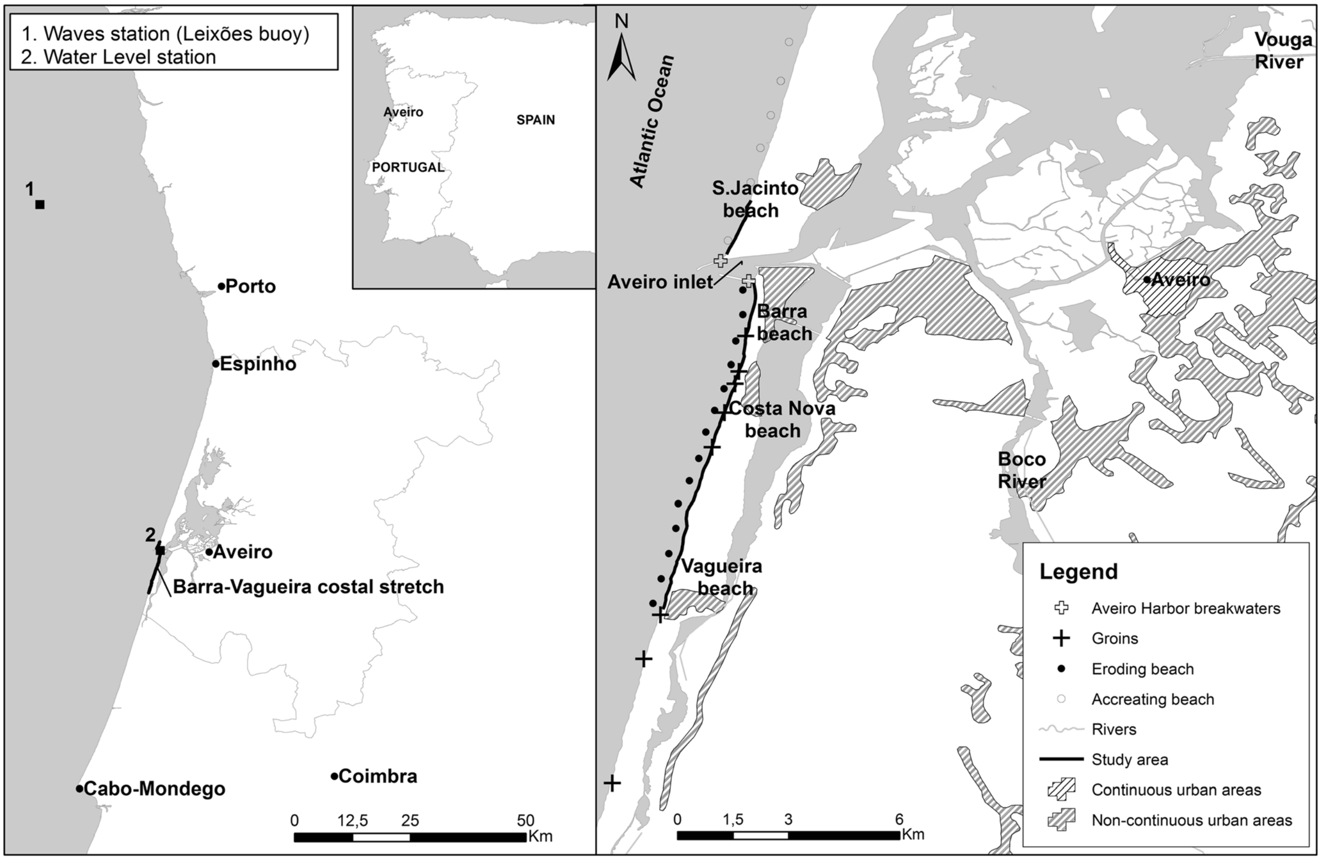


Fig. 1 Map of Barra-Vagueira coastal stretch (Palalane et al., 2016)

In terms of sediments dynamic, as the longshore sediment transport is interrupted by the Aveiro Harbor breakwaters, an intense accumulation of sand occurs on the updrift (north) side and a significant retreat of the shoreline is occurring on the downdrift (south) side. This retreat is controlled by groin fields and longitudinal revetments along Costa Nova and Vagueira beach (Figure 1). According to the long-term shoreline evolution study developed by Veloso-Gomes *et al.* (2006), for a period between 1980 and 1990, the shoreline retreat rate in Costa Nova beach and Vagueira beach is estimated in 3.7 and 3.9 m/year, respectively, whereas Barra beach present a retreat rate of about 0.3 m/year (Palalane *et al.*, 2016).

Physical setting

In general, the Portuguese west coast, which includes the coastal region of Aveiro, is heavily exposed to waves generated in the North Atlantic. The wave climate is essentially characterized by components of distant generation. These components have higher wave heights and longer periods than those that would be generated by action of the local wind. The mean significant wave height is around 2–3 m while the mean period is between 8 and 12 s. The largest waves, especially common in winters during storm events, are incident from northwest and may reach 8 m, persisting for up to 5 days (Pires 1989; Coelho 2005; Coelho et al. 2009b). The tide regime in Aveiro is semi-diurnal, with neap and spring tidal amplitudes ranges of 2 and 4 m, respectively.

For the northwest portuguese coast, the wave regime is generally characterized by data recorded at Leixões buoy, operated by the Portuguese Hydrographic Institute (IH). This buoy is located 78 km NNW from Aveiro, at a depth of 83 m (Figure 1) and its measurements are considered to be representative for the offshore wave conditions at the study site (IH, 2015).

Time series of wave climate between Sep-09 and Apr-15 were provided by the Portuguese Hydrographic Institute and analyzed to support the present study. The data set encompassed records of peak period (T_p), average direction associated to the peak period (Tht_p), significant wave height (H_s) and average of the periods corresponding to H_s (TH_s) mostly at intervals of 3 h (IH, 2015). Records collected at intervals of less than the usual 3 h and with maximum wave height greater than 5 m were considered storm records. If 10 or more storm records exist during a time interval equal or greater than 8 h, the storm was defined persistent. Figure 2 displays the distribution of the wave directions and wave heights for normal and persistent storm conditions for the period between Sep-09 and Apr-15.

Time series of 3-h records showed that waves coming from the NW sector are the most frequent (corresponding to 46% of records), followed by WNW and NNW directions, with 29% and 11% of the observations, respectively. The dominant wave height classes are situated between 0.5 m and 2.5 m and represent 72% of the 15,296 records. The maximum value of the average significant wave height was around 8.89 m and has been registered in March of 2014. In persistent storm conditions, waves are more oriented towards the south, increasing the percentages of occurrence of the NW and WNW sectors to 56% and 37%, respectively, and decreasing the significance of the NNW quadrant to 1%. Significant wave heights below 2.5 m have no representativeness, acquiring importance above 3.5 m. The most common class is located between 4.5 m to 6.5 m, with 74% of the 5270 storm records.

The wave periods distribution showed that more than 85% of the records present peak periods lower than 12 s, being the dominant class located between 8 s and 10 s, with 32% of the observations. In storm situations, this range of values (below 12 s) is only representative of 45% of the observations, with no records lower than 8 s. The most frequent class is the 12 s to 13 s (about 22%).

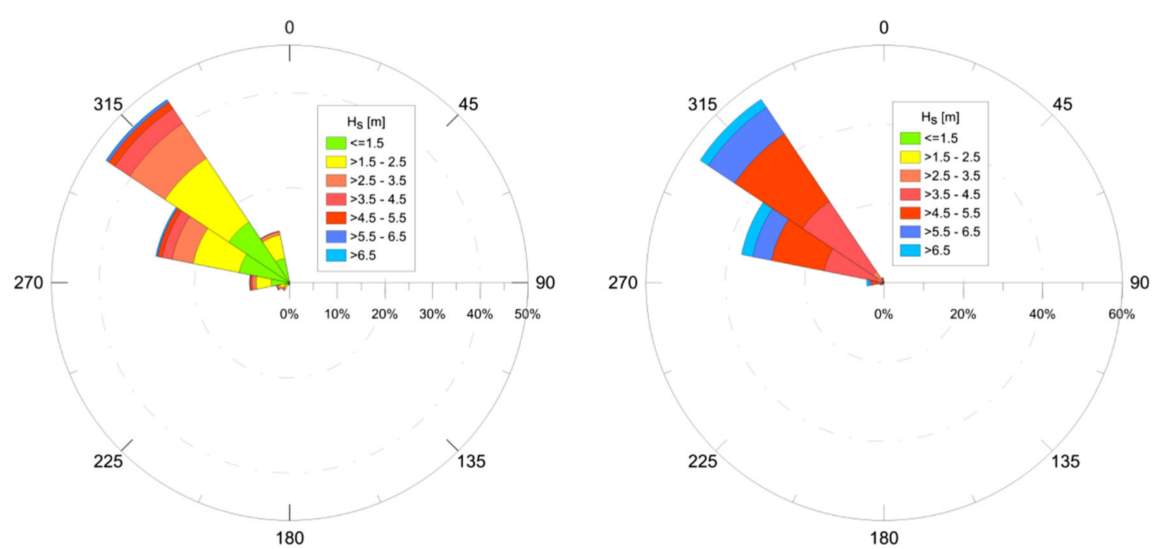
The higher-energy wave conditions were registered in Nov-10, Jan-13 and Mar-14 (see peaks of maximum H_s in Figure 3). According to some media and APA reports, the major storms recorded between Dec-13 and Mar-14 (the most energetic period, with an average significant wave height of 3.38 m) hit Costa Nova beach causing abrupt changes on the dune system.

Harbor interventions and monitoring

In order to control beach erosion along the Barra-Vagueira coastal stretch and improve the conditions of the Barra navigation channel, two major projects were undertaken by the Aveiro Harbor Administration – APA (beyond the regular activities of navigation channel maintenance) between 2009 and 2015: "Dredging of Barra with reinforcement of the dune system", in 2009, and “Reconfiguration of Barra north breakwater”, in 2012–2013 (APA, 2012; APA, 2013).

The main objective of the first project was the dredging of 1 million m^3 of sand (performed in two time periods, see Table 1) from the bottom of the inlet entrance of the Aveiro Harbor and the use of the resulting sand to reinforce the littoral system in the Costa Nova beach. The second major project conducted by APA corresponded to the extension of the north breakwater by 200 m, realignment and dredging of the navigation channel in order to ensure a bottom level of −12.5 m (CD). The dredged material from the channel and breakwater extension was deposited at the subaqueous portion of the beach profile in two main sites. The first site (DA1) was limited by the south breakwater and the 1st groin of Costa Nova beach (2012–2013), between 4 and 7 m water depth (see Figure 4). The second site (DA2) was bounded by the 3rd and the 5th groins of Costa Nova (counting from north to south, Figure 1), at a depth between 2 and 5 m contours.

The following table synthetizes the information related to the dredging and dumping operations carried out at Barra and Costa Nova beaches during 2009–2015. Some of the information described was concatenated based on the interpretation of design elements made available by APA.



a) *Normal conditions (3-hours interval)* b) *Persistent storm conditions (30-minutes interval)*

Fig. 2 Wave rose with energy based on significant wave height, H_s, measured at Leixões (2009–2015)

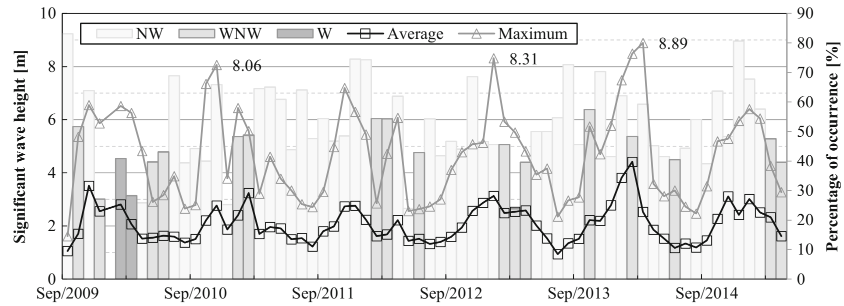


Fig. 3 Monthly significant wave height and corresponding dominant sector of the wave direction

Since 2009, the evolution of the dumping areas (defined for fill operations in connection to the main projects undertaken at the study area) has been accompanied by APA through monitoring campaigns. Hydrographic surveys have been collected annually and just before and after the placement of the fills within the dumping areas, along a total period of about 6 years (Sep-09/May-15). Table 2 summarizes the details of the surveys collected in the field (dates and locations).

Figures 5 and 6 show the timeline of each nourishment and survey performed in DA1 and DA2, respectively

Methodology

GIS tecnhiques were applied to investigate the sediment dynamic and bathymetric evolution of two main dumping areas

Table 1 Dates, provenience, location and volumes of dredging/dumping operations (APA, 2013)

Date of dredging/dumping		Provenience	Location	Volumes (m^3)	Total anual (m^3)
Year	Month				
2009	April/May	Navigation	DA2	500,000	1,000,000
	September/October	Navigation	DA2	500,000	
2012	June	Breakwater construction	DA1	169,218	169,218
2013	May	Breakwater construction	DA2	66,725	1,604,917
	May	Navigation	DA1	79,061	
	July	Navigation	DA1	251,721	
	July	Navigation	DA2	1,008,113	
	October	Navigation	DA2	97,724	
	November	Navigation	DA2	101,573	
2014	September	Navigation	DA2	64,781	531,903
	October	Navigation		51,461	
	October	Navigation		59,155	
	November	Navigation		141,000	
	November	Navigation		7285	
	December	Navigation		101,692	
	December	Navigation		6529	
	December	Navigation		100,000	
2015	May	Navigation	DA2	137,775	432,507
	November	Navigation	DA2	25,543	
	November	Navigation		125,403	
	November	Navigation		37,396	
	December	Navigation		56,782	
	December	Navigation		49,608	

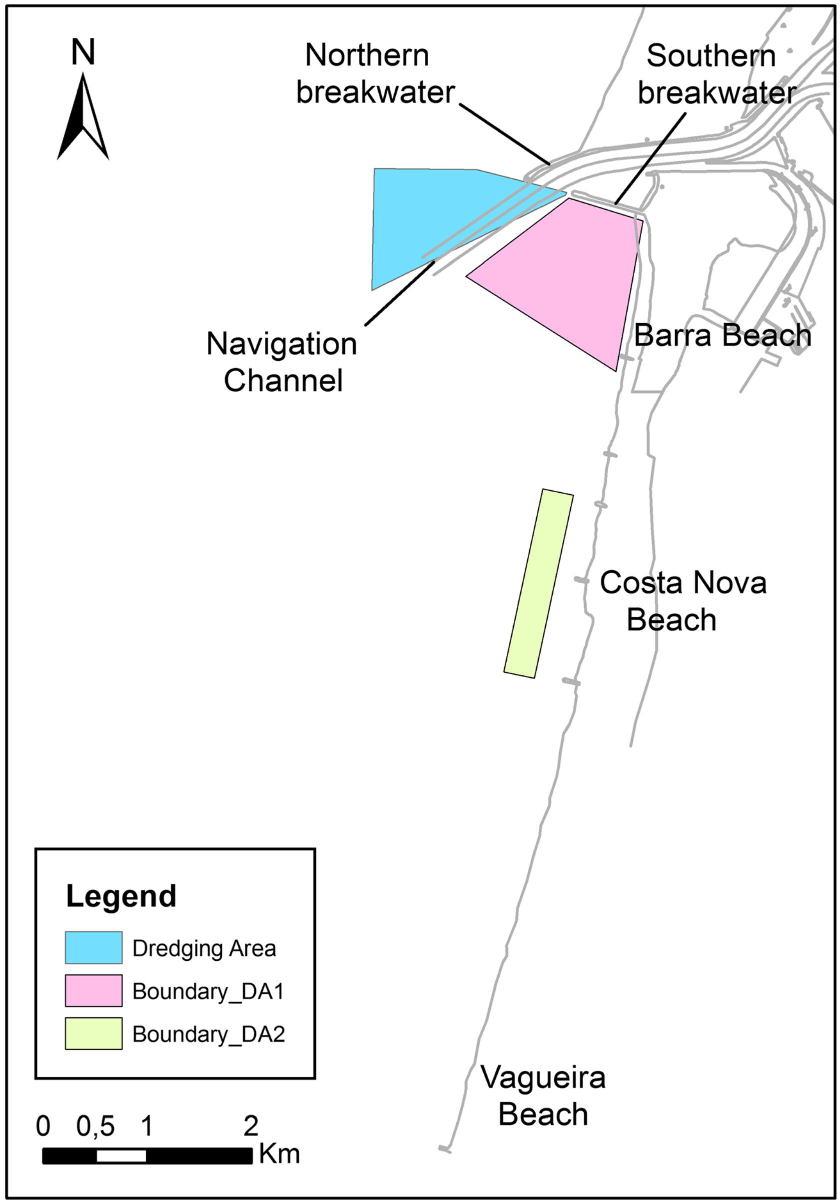


Fig. 4 Location plan of the dredging and deposition areas and cross-sections (APA, 2012; APA, 2013)

(DA1 and DA2) between 2009 and 2015. A database encompassing the hydrographic surveys collected in the field (mostly before and after the nourishment interventions) were used and georeferenced in Geographic Information System (ArcGis).

The field data related to both areas was processed individually. The first approach involved the definition of a common area (CA) covered by all the available surveys for each dumping area (DA1 and DA2) in order to quantify the sediment volume variation in time. As four main surveys collected for DA2 covered a very small area, two main common areas were defined: one considering all surveys available with exception of Jan/14 (the most restricted survey) and another one excluding the survey data collected in Dec/10, Nov/11, Nov/13 and Jan/14. Figure 7 displays the location of the common areas analyzed for DA1 (CA1) and DA2 (CA2, CA3).

The common area for dumping area 1, CA1 (Figure 7a), has 0.43 km^2, and is bounded in the longshore direction by the south breakwater of Barra and the 1st groin of Costa Nova, between the 2.5 and 8.5 m water depth level. The first (CA2) and the second (CA3) common area defined for DA2 have 0.53 and 1.05 km^2, respectively, and are both located between the 3rd and the 5th groin of Costa Nova. In cross-shore direction CA2 is limited by the levels −2 and −9 m (CD), while CA3 covers deeper areas, reaching approximately −10 m (CD). The reference situation was taken to be May 2012 for DA1 and September 2009 for DA2, corresponding each one to the date of the first survey carried out in each area (Figure 7).

Table 2 Dates and locations of hydrographic surveys (APA, 2013)

2009	2010	2011	2012	2013	2014	2015
20/09 (DA2)	Dec (DA2)	Nov (DA2)	24/05 (DA1)	19/04 (DA2)	27/09 (DA2)	02/01 (DA2)
29/10 (DA2)			24/06 (DA1)	27/05 (DA2)		01/05 (DA2)
			30/10 (DA2)	26/06 (DA1 and DA2)		
				23/07 (DA1 and DA2)		
				24/11 (DA1 and DA2)		

Digital elevation models were generated by applying an inverse distance weighting (IDW). With the surfaces obtained, sediment volume balances were computed between survey dates, within the common areas boundaries. When possible (depending on the surveying coverage), altimetric comparisons were performed in larger areas than the common areas to enable a better understanding of the fill response. Surveys carried out before and after the fill placement were used to evaluate the short-term behavior of the fills whereas surveys more spaced in time were used to investigate the medium/long-term response of the fills.

Results

The results are exposed and interpreted based on a perspective of chronological morphological changes, following three main viewpoints: general evolution of the common areas, and short-term and medium/long-term effect of the sand nourishments. Sediment budgets variations within the common areas are summarized in Fig. 8. Sea bed elevation comparisons showing the morphologic response of the dumping areas in short- (just after the fills) and medium/long-time scales are displayed in Fig. 9 to Fig. 12.

Five hydrographic surveys were collected between 2012 and 2013, in DA1. The evolution of the common area (CA1) show positive sediment balances in almost all the periods between surveys, being the only exception to this pattern the period between July and November 2013 (which presents a small loss of 0.02 Mm^3 of sand). To investigate the short-term response of DA1, two altimetric comparisons encompassing one month interval were generated (Figure 9). The accretion of 0.16 Mm^3 registered between May and June 2012 is in good agreement with the sand volume dumped in June (169,218 m^3). Nevertheless, the volume increase that was registered between June and July 2013 (0.15Mm^3) only corresponds to 61% of the nourishment carried out during that period (251,721 m^3) meaning that in one month about 39% of the nourished volume moved out from the surveyed area.

The analysis focusing the medium-term behavior of the DA1 was also possible for two periods: Jun/12 - Jun/13 (1 year) and Jul/13 - Nov/13 (five months). The increase of approximately 0.08 Mm^3 registered one year after the first fill (Jun/12 - Jun/13) is coincident with the sediment volume which had just been dumped in May 2013 (79,061 m^3). This correspondence of volumes suggests that the material dumped in 2012 (first fill in this area) remains within the common area, although the Fig. 10a indicates that the dumped sand has been moved alongshore. The large sand mass was conducted mostly to south, being also possible to identify some accretion at north. This particular distribution of the sand can be related to diffraction currents generated by the northern Aveiro Harbor breakwater which possibly can invert the sediment transport direction in its shadow area. A divergence hotspot (site of greater erosion that limits the exposed area and the breakwater shadow area) can also be identified in Fig. 10a. Outside the

Fig. 5 Timeline for nourishments and surveys for dumping area 1 (DA1)

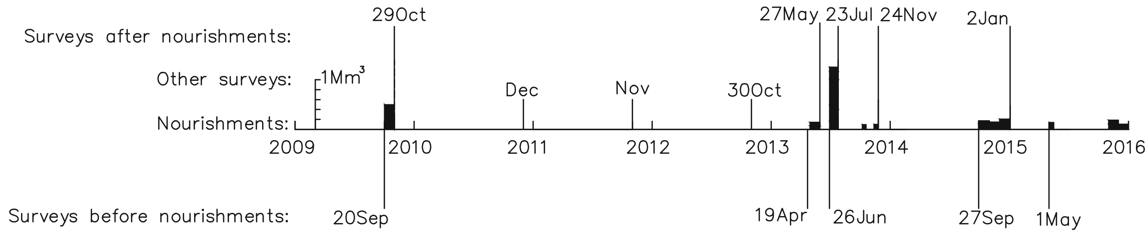
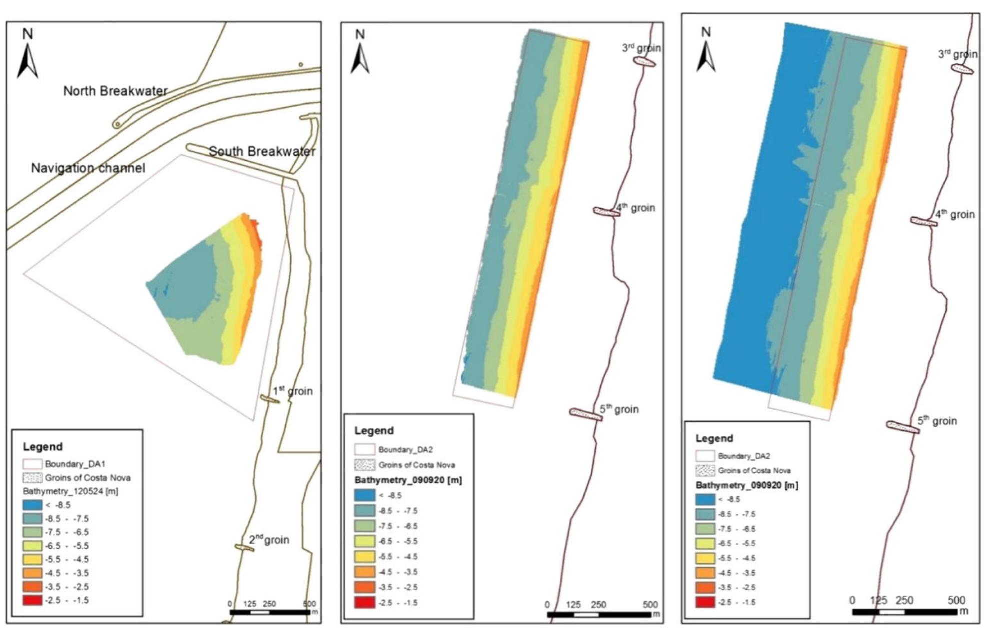


Fig. 6 Timeline for nourishments and surveys for dumping area 2 (DA2)

boundaries of the common area, the effect of the diffraction currents in the bottom can be recognized in Fig. 10b, as well as the non-linear sand nourished distribution. The sand spreading suggests an onshore sand volume migration larger than the offshore. The loss verified between July and November (Figure 10b) is small and corresponds to only 8% of the last fill in July 2013. Overall, the erosion or accretion registered in DA1 decreases and increases respectively, if the analyzed area is extended (see Fig. 9 and Figure 10), meaning that the sediments remain in the local area, although outside its boundaries. In total, between May/12 and Nov/13, the cumulative volume into the common area was calculated in 0.37 Mm^3 and corresponds to 74% of dumping material.

For dumping area 2 (DA2), thirteen surveys were available and analyzed. According to the Fig. 8, the evolution of the common areas (CA2 and CA3) defined for DA2 is mostly consistent, presenting the same trends of erosion/accretion. Short-term changes in sea bottom elevation were investigated through altimetric comparisons just before and after the nourishment placement, corresponding to approximately one month time interval (Fig. 11a, Fig. 11b and Figure 11d). The effect of the placement of the fills can be easily identified by the central darker spots (red) within the limits of the dumping area (DA2). In general, the nourishment mound, placed to form nearshore berms, immediately began eroding, being possible to identify a seaward migration of the nourished sand resulting from offshore directed currents. As offshore sediment transport is not a continuous phenomenon (Ruessink and Terwindt, 2000) but an intermittent process confined to high-energy events, the moderate-energy waves registered by the Leixoes buoy in Jun-13, with a maximum significant wave height of 4.17 m can explain this evident pattern identified in Fig. 11c and Fig. 11d. This record corresponds to the most energetic event recorded in June over the almost 6 years of observations. The results of the sediment budgets calculated in CA2 (the smaller common area) only corresponds to 67% (Sep/Oct 2009) and 53% (Jun/Jul 2013) of the balance calculated in CA3, which means that an average of 40% of the dumped material moved out from the boundary of CA2 during only one month (see Fig. 8 and Fig. 11a and Figure 11d). In addition, between June and July 2013 (see Figure 11d) approximately 51% of the fill volume was not detected within the surveyed boundaries. It is hypothesized, although not verified, that part of the fill material had been transported towards to the beach (increasing the berm width) since during Jul-13 the beach profile was affected by short-waves conditions



a) *24-May-12 (CA1)* b) *20-Sep-09 (CA2)* c) *20-Sep-09 (CA3)*

Fig. 7 Common areas for DA1 and DA2 (bathymetry in the reference situation)

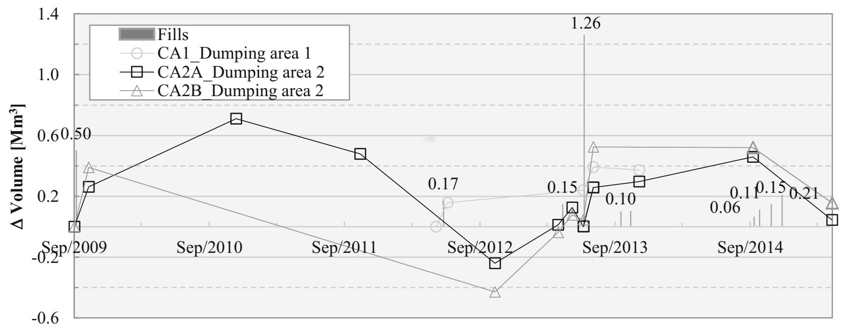
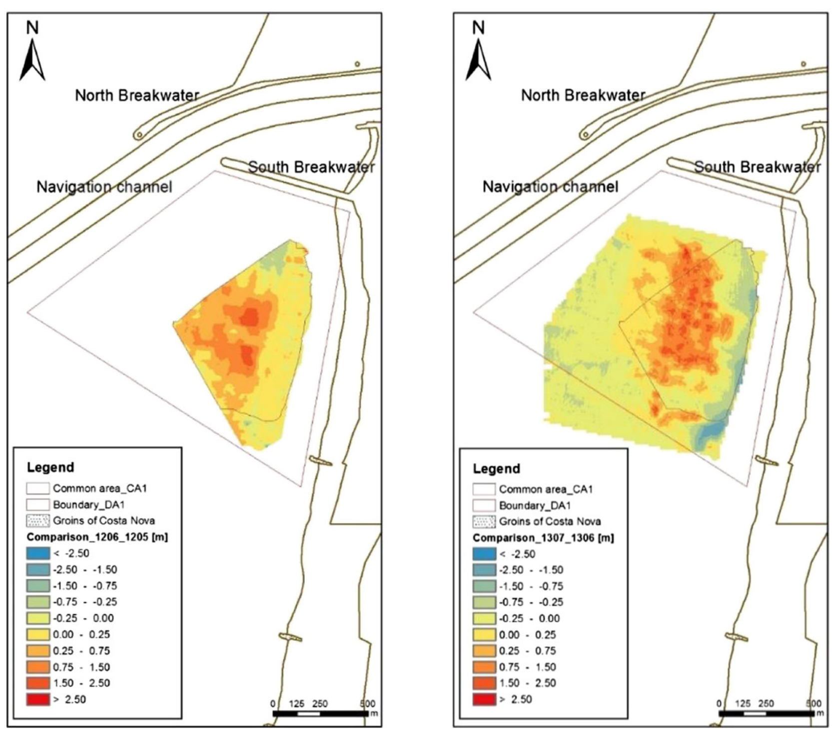


Fig. 8 Sediment balance of the dumping areas between Sep-09 (reference situation to DA2) and May-15. The bars correspond to the nourishments and the marks (triangles, circles and squares) to the survey events

(promoting onshore sediment transport, see Figure 3). Figure 11c displays the evolution of the nourishment carried out in May 2013 (66,725 m^3) two months later. This map evidences a offshore migration of the nourished sand, with losses around 0.03 Mm^3 within the CA3 (47% of the nourished material in May 2013).

Bathymetric analysis ranging from months to a few years were also carried out for DA2 (see Figure 12). Four main bathymetric comparisons were generated to address the impact of the first significant fill undertaken in DA2 (2009): Oct/09 - Dec/2010, Oct/09 - Nov/11, Oct/09 - Oct/12, Oct/09 - Apr/13 (Fig. 12a to Figure 12d). Results until Nov-11, reveal that the nourished sand (dumped in Sep/Oct-09) eroded while sand accumulated nearshore, contributing to positives sediment budgets around 0.45 and 0.22 Mm^3 in Dec-10 and Nov-11, respectively (Figure 8). The high-energy 'winter' conditions registered during Nov-10 (see peak of H_s in Figure 3) offers an explanation for the fact that a large subaqueous sand barrier was found in Dec-10. In fact, during energetic events (characterized by higher waves and water levels), a longshore sand bar typically form at Aveiro coast, as a result of a net seaward cross-shore sediment movement, promoting erosion of the summer profile (calm wave conditions). Thereby, the intense accumulation of sand identified in Fig. 12a is clearly attributed to seasonal morphological changes of the beach (resulted from exchange of sand between the summer berm and the winter offshore bar). However, it is also likely that the nourished volume had partially been transported shoreward (helping to feed the bar) and

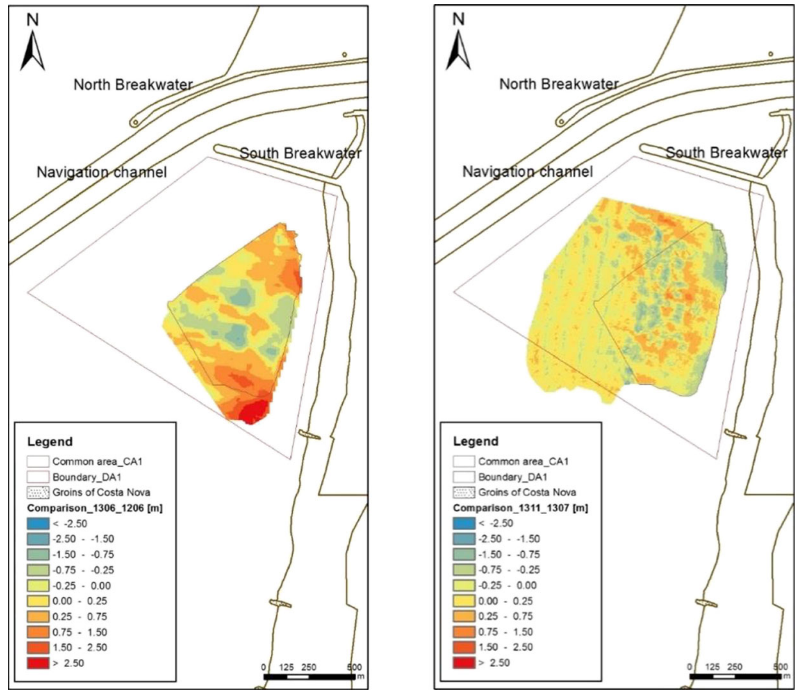
Fig. 9 Short-term evolution of DA1 (bed elevation comparisons between surveys)



a) *May and June 2012 (one month)*
Area=0.48 km^2; ΔVolume=0.16Mm^3
Nourishment volume= 169 218 m^3

b) *June and July 2013 (one month)*
Area=1.11 km^2; ΔVolume=0.11Mm^3
Nourishment volume= 251 721 m^3

Fig. 10 Medium/long-term evolution of DA1 (bed elevation comparisons between surveys)



a) *June 2012 and June 2013 (one year)*

Area=0.52 km^2; ΔVolume= 0.16Mm^3
Nourishment volume= 79 061 m^3

b) *July and November 2013 (five months)*

Area= 0.93 km^2; ΔVolume=-0.01 Mm^3
Nourishment volume= 0 Mm^3

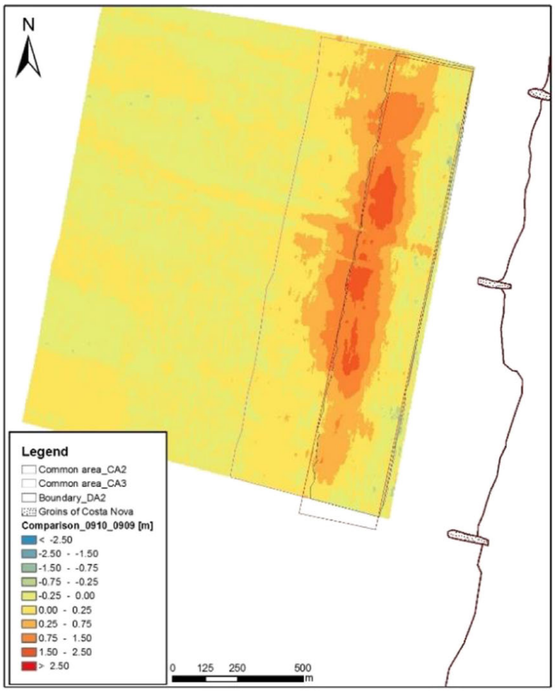
seaward (storing material at deeper waters) due to delicate balance of opposing sediment transport components along the profile highly dependent of the forcing conditions.

Two years later of the first fill (Fig. 12b) no submerged bar was detected by the hydrographic survey (Nov/11). However, it was identified a general profile bed elevation (above 6 m water depth) in relation to Oct/09. This behavior is in agreement with the observed in Figure 12b, suggesting that sediments had migrated in onshore direction.

Three years after the dumping operations, in 2009, more than 0.80 Mm^3 of sediments move out from the boundaries of CA3 (Figure 8), but approximately 17% (0.14Mm^3) of the “lost” sediment was stored below the level − 9.5 m (CD). In Fig. 12c, although the nourishment has eroded, it is possible to identify a slight elevation of the sea bottom for deeper areas which might be associated to a long-term effect of the fills. The negative sediment balance calculated within CA3 between Oct/09 and Apr/13 is around 0.43 Mm^3 (Figure 12d), which corresponds to approximately half of the variation in 2012. This difference is probably seasonal and a result of the comparison between a winter profile (Apr/13) and a summer profile (Oct/09).

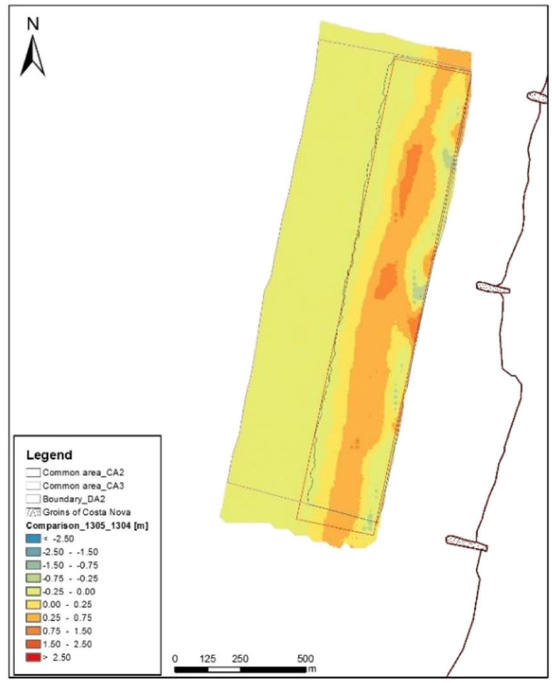
Next fills of DA2 were carried out in May, July, October and November of 2013, being the second one the most significant (1,008,113 m^3). Figure 12e indicates an accretion of sediments (within CA2) close to 0.04Mm^3 of sand. This value corresponds only to 20% of the total nourished volume carried out in Oct-Nov 2013. Extending the temporal scale, the general evolution of this fill was analyzed between Jul/13 and Sep/14 (Fig. 12f). During this period, nourishments were carried out only in Oct-Nov 2013 (199,297 m^3). As expected the dumped material was subjected to the natural adjustment under local wave conditions, which contributed to a lost volume around 0.05 Mm^3 (within the CA3). Figure 12f suggests that the dumped sediment was driven shoreward forming a breaking sand bar. However, as the survey collected in 2014 was performed in September (time that the beach profile is in a typical summer state), such sand barriers at surf zone are not expected, suggesting that this sand barrier may be a storage of nourished sand. Also, as the volume balance within CA3 shows a negative value during this period and more than 51% of the fill was not detected one month later of the fill (Figure 11d) it is expected that the part of this fill volume had been transported to the subaerial portion of the beach profile and also driven to deeper waters.

As the survey carried out in Jan/15 (after the fill period) covered a smaller area (Figure 12g), a comparison between Sep/14 and May/15 was established to investigate the impact of the fills performed during Sep-Dec 2014. The sediment volume balance was calculated in −0.36Mm^3 which means that there is no signal of the artificial volume added.However, Fig. 12h suggests that a large concentration of sediments can be hidden outside the common areas limits



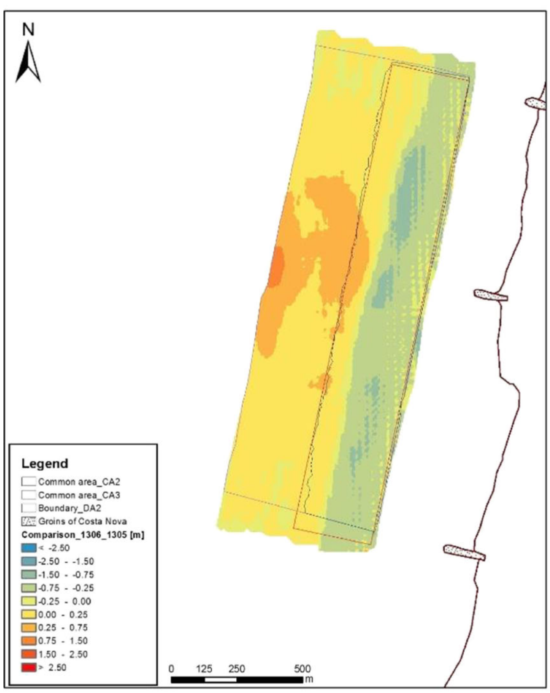
a) *September and October 2009 (one month)*

Area=2.52 km²; ΔVolume=0.36Mm³
Nourishment volume= 500 000 m³



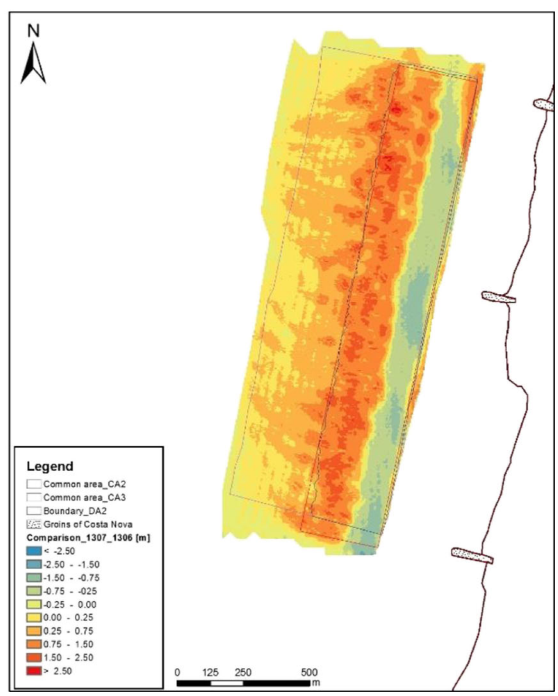
b) *April and May 2013 (one month)*

Area=1.17 km²; ΔVolume=0.13Mm³
Nourishment volume= 66 725 m³



c) *May and June 2013 (one month)*

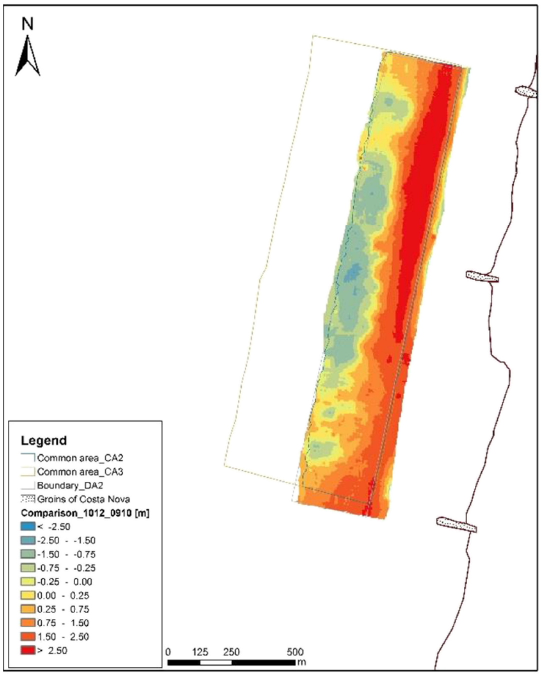
Area=1.17 km²; ΔVolume= -0.08Mm³
Nourishment volume= 0 m³



d) *June and July 2013 (one month)*

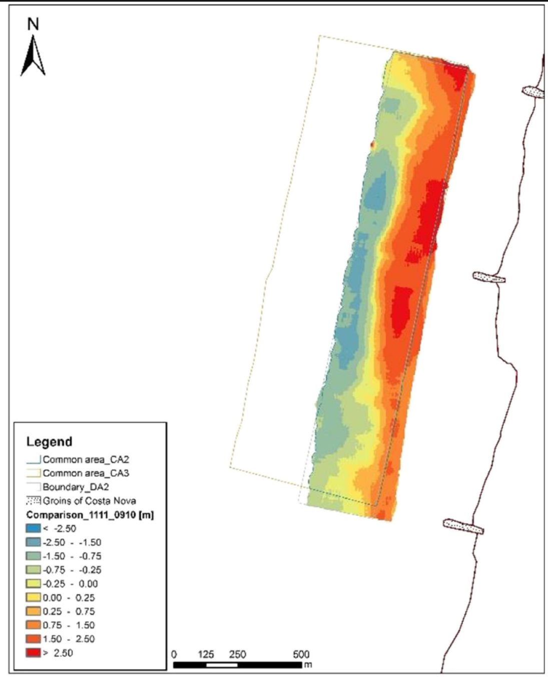
Area=1.30 km²; ΔVolume=0.50Mm³
Nourishment volume= 1 008 113 m³

Fig. 11 Short-term evolution of DA2 (bed elevation comparisons between surveys)



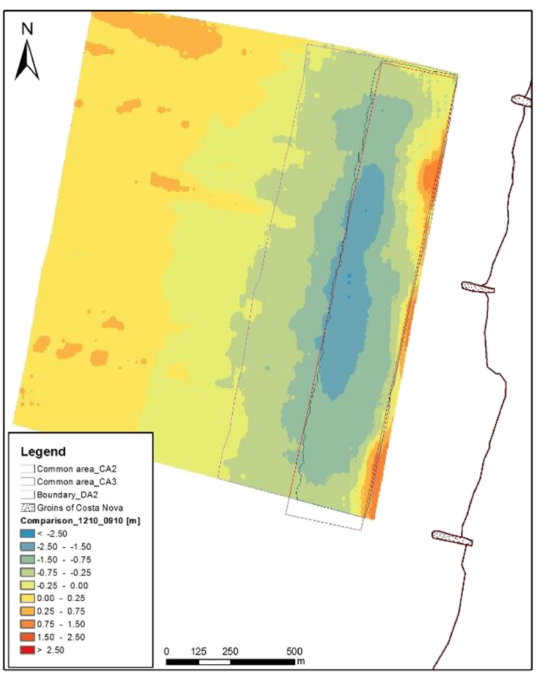
a) *October 2009 and December 2010 (fourteen months)*

Area= 0.64 km²; ΔVolume= 0.57 Mm³
Nourishment volume= 0 m³



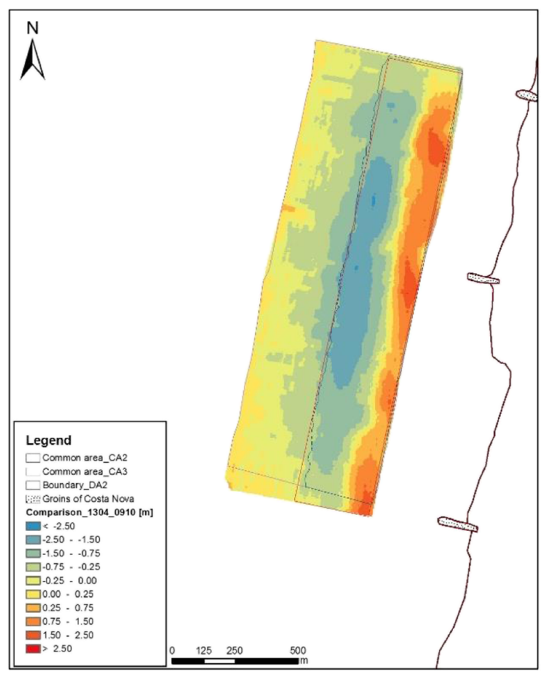
b) *October 2009 and November 2011(twenty-five months)*

Area= 0.61 km²; ΔVolume= 0.30 Mm³
Nourishment volume= 0 m³



c) *October 2009 and October 2012 (three years)*

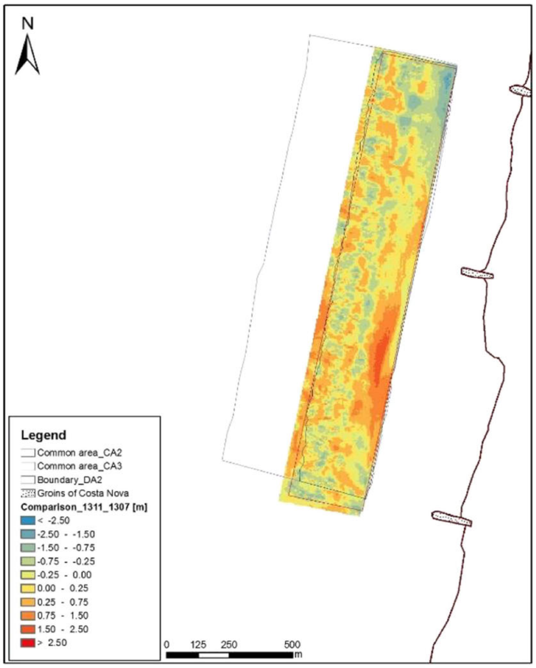
Area= 2.52 km²; ΔVolume= -0.68 Mm³
Nourishment volume= 0 m³



d) *October 2009 and April 2013 (three and half years)*

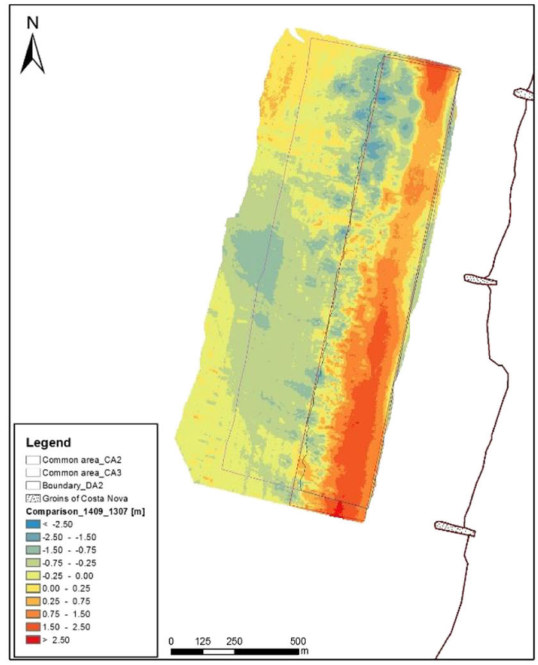
Area= 1.09 km²; ΔVolume= -0.39 Mm³
Nourishment volume= 0 m³

Fig. 12 Medium/Long-term evolution of DA2 (bed elevation comparisons between surveys)



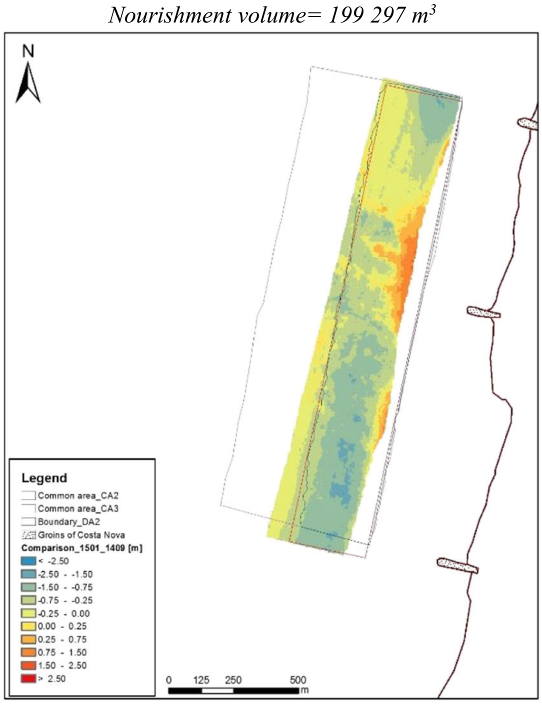
e) *July and November 2013 (four months)*

Area= 0.63 km²; ΔVolume= 0.04 Mm³
Nourishment volume= 199 297 m³



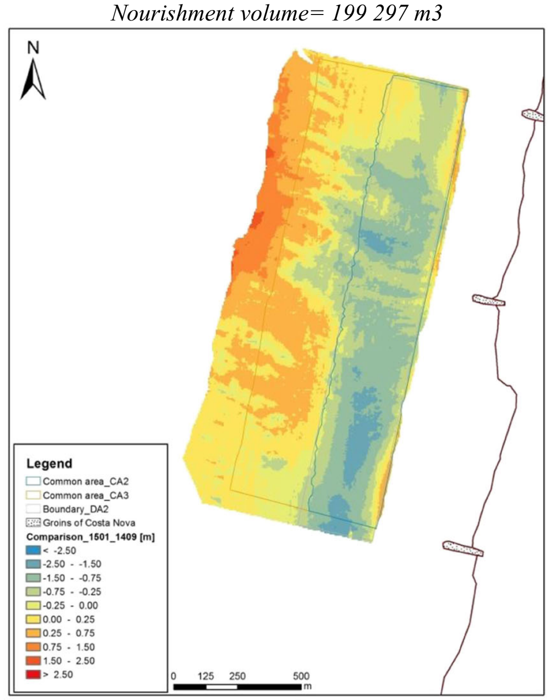
f) *July 2013 and September 2014 (ten months)*

Area=1.40 km²; ΔVolume= -0.06 Mm3
Nourishment volume= 199 297 m3



g) *September 2014 and January 2015 (four months)*

Area= 0.56 km²; ΔVolume= -0.25 Mm³
Nourishment volume= 531 903 m³



h) *September 2014 and May 2015 (seven months)*

Area= 1.40 km²; ΔVolume= -0.28 Mm³
Nourishment volume= 531 903 m³

Fig. 12 continued.

(there is a strong sand accumulation that could not be completely represented).

The general sediment balance between September 2009 and May 2015 in CA3 is approximately 0.15 Mm^3, which corresponds to 7% of the total dumped sand volume (about 2.3 Mm^3 of sand).

Discussion

According to Verhagen (1996) and Pinto *et al.* (2015), nourished beaches have expected short-term losses (sand transfer to subaqueous portion), that range between 10% and 20%. This is assumed as a typical morphological response of the beach profile, due to its natural adjustment under the local morphodynamic conditions. Past nourishments experiences in Portugal, more specifically in less energetic coastal areas (Algarve), also indicate that subaerial losses are around 10 and 27% (APAmbiente, 2014). Recent interventions in Costa da Caparica suggest that early subaerial beach losses are about 30% (Pinto *et al.*, 2015). Such analysis carried out for Costa Nova beach revealed that short-term losses can be very influenced by the time and place that the fill material is dumped. In general, the study undertaken with focus on the morphological development of the dumping areas point out that initial losses (during the first month) can range between 0 and 50% of nourished volume, meaning that the sediment dynamic under surf zone conditions can be very strong during high-energy periods. Also, the fact of some dumping operations had been carried out during transition and winter periods (where the beach morphology is significantly affected by high-energy events) along the subaqueous portion of the profile (as nearshore deposits) may have induced to a quick redistribution of the fill material, explaining these substantial short-time losses and also the incapacity to track the ultimate fate of the nourished sand under different forcing conditions. The performed analysis leads to believe that if the major underwater fills had been placed on the subaerial beach in late summer, when the berm width reaches its maximum, as suggested by Yates *et al.* (2009), when studying fill behavior at a southern California beach, the fill material may have taken longer in subaerial beach profile. However, the outcomes from different design schemes and different timings for the fill placement are still poorly understood and can only be speculated about (Yates *et al.*, 2009; Jacobsen and Fredsoe, 2014). Also, the behavior of such interventions on sandy beaches with high cross-shore fluxes (like the ones along the Aveiro coast), arising from strong seasonal cycles seems to differ significantly from other coastal systems under low-energetic forcing conditions.

Conclusions

In this paper, a general analysis about the morphological evolution of two nourished areas is presented. The analysis was based on hydrographic surveys collected by Aveiro Harbor Administration, mostly, before and after dredging and dumping operations. The information available was compiled in a database and used to investigate the short- and medium/long-term response of fills differing in volume and construction period.

Despite the limitations around the field data, intrinsically related with the temporal and spatial resolution of the surveying, bathymetric data analysis highlighted strong seasonal fluctuations in sand levels highly affected by seasonal fluctuations in wave energy, with energetic storms during winter and low-energy waves during summer. Initial changes of the fill material in the dumping areas evidenced dominant patterns of offshore directed losses as well as a high distribution of the nourished volume which might be attributed to the underwater approach adopted by APA to perform artificial nourishments in a quite energetic environment.

The dumping area DA2 presented a larger sediment volume loss than DA1 which may be related to its location, since DA1 is under the shadow of the Aveiro Harbor breakwaters, benefiting from protection against storms. Overall, both short- and medium-term analyses in DA2 suggested that the fill material was quickly dispersed, suggesting a small impact in the coastal system. Also, due to high cross-shore fluxes of sediments captured, cross-shore material exchanges resulted from seasonal variations seems to prevail and misrepresent some sediment budgets if the surveyed area is not comprehensive enough.

Clearly, more systematic surveying, covering all seasonal patterns and specially the occasions before and after nourishment operations, is required to get a better description of the cross-shore and longshore sediment transport processes taking place, in order to capture important beach changes (such as storm-induced changes) as a response to the incident waves and to track the ultimate fate of the nourished sand. Extend the surveys in both onshore and offshore direction is recommended to get a clear understanding of the cross-shore fill redistribution. Also, the extension of the monitoring coastal stretch to southern beaches (downdrift) will allow to investigate with confidence the feeding properties of the fills, giving guidance if the sediments have been conducted to the south, recovering and reinforcing eventually other critical areas (such as Vagueira beach).

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PAPER III

Marinho, B., Coelho, C., Larson, M., Hanson, H. **(2017);** *Monitoring the Evolution of Nourished Beaches Along Barra-Vagueira Coastal Stretch, Portugal*. Ocean & Coastal Management Journal, 157, 24-29 pp. DOI: 10.1016/j.ocecoaman.2018.02.008

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Monitoring the evolution of nearshore nourishments along Barra-Vagueira coastal stretch, Portugal

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ABSTRACT

Maintenance of existing harbors implies regular dredging activities. Where the combined use of dredging and disposal of dredged material on nearby sediment-starved beaches can induce major changes in the beach morphology and generate unexpected impacts in the environment, monitoring becomes a concern. This paper was designed to analyze, interpret and evaluate a set of monitoring data collected along a regular-nourished coastal stretch with dredged sand (Barra-Vagueira coastal stretch, northwest coast of Portugal), surrounded by an energetic hydrodynamic environment with a scarce natural sediment input. Based on a field data set, collected between 2009 and 2015, the present study brings together a set of correlated analyses, intended to assess the morphodynamic evolution of the fills as well as their impact to the adjacent coast. The available data set encompasses topo-hydrographic surveys collected for 12 cross-sections (with 1 km spacing) distributed along the coastal stretch and bathymetric measurements collected for the dumping areas. Considering the concurrent offshore wave forcing, dominant temporal and spatial patterns, morphological changes, evolution trends, sediment budgets, and short- and medium-term responses of the fills are investigated by the use of ArcGIS tools and application of a multivariate statistical method based on Empirical Orthogonal Functions (EOFs). Overall, during the monitoring period, almost 2.8 Mm^3 of sand was dumped in different locations and periods to control the erosion observed downdrift of the inlet. However, bathymetric surveys and profile indicators still point out the erosional longshore pattern diagnosed decades ago as a result of a negative longshore sediment balance. Observations also revealed that short-term changes arising from the seasonal cycles of cross-shore material exchange are mainly linked to the largest variations in the beach profile shape, also affecting the sediment budget. Profiling indicated cross-shore volume variations ranging from ± 250 m^3/m and ± 1500 m^3/m in the subaerial and subaqueous portion of the profile, respectively, along the monitored period. After the first completed seasonal cycle the sand bar, artificially created by the nourishments, could not be visually detected in the profiles, suggesting a cross-shore redistribution of the fill material. All the analyses developed in this paper stress the importance of establishing proper monitoring programs based on adequate surveying instruments and data collection strategies, in order to ensure high-density data that could be used in support to the decision-markers.

1. Introduction

Dredging operations are regularly undertaken for maintenance of existing harbors. In order to maximize the benefit taken from maintaining depths or deepening activities of navigation channels, the dredged material is typically reintroduced into the littoral system through direct placement at downdrift areas, where beaches have become depleted of material. In this respect, monitoring becomes a concern since the combined use of dredging and disposal of dredged material may induce major changes in the beach morphology and generate unanticipated impacts in the environment, especially in a long-term perspective (Monge-Ganuzas et al., 2013; Mateus et al., 2016; Rehitha et al., 2017). Although the potential use of dredged material for sediment replacement of eroding beaches is widely recognized, there is little comprehensive guidance available for engineers or planners regarding an adequate monitoring plan.

Monitoring is particularly valuable since it serves to objectively document and assess the performance of the project, determining how well it fulfills the requirements for which it was designed, and evaluate related impacts on adjacent shorelines (Capobianco et al., 2002; Gravens et al., 2003; Vacchi et al., 2012). Analysis of monitoring data can also shed light on an adequate frequency of surveying, or even on

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the natural conditions that prompt the need for improving the project performance or developing potential design alternatives (Capobianco et al., 2002; Castelle et al., 2009; Vacchi et al., 2012). Particular data of interest include topo-bathymetric surveys, waves and water levels, and characteristics of native and placed sediments. Beach profile surveys are essential for estimation and documentation of fill volumes and changes in the beach cross-section, allowing the prescribed sectional fill volume to be verified in compliance with the design specifications. Wave and water level data also provide valuable information for understanding project behavior and formulating solutions by establishing cause-and-effect relationships between the forcing conditions and the measured beach response. Beach sediment sampling is needed to determine sediment properties, for example, the grain-size distribution. This is of particular importance when the nourished and the native sand have very different properties, which can directly affect the beach profile shape and influence the fill evolution (Creed et al., 2000; Gravens et al., 2003).

The dynamic behavior of nourished beaches as well as dredged areas together with the need to ensure project functionality over the design life requires a systematic monitoring plan to be established. However, in many cases they are not well planned or carried out in a comprehensive manner. A weak point of many monitoring schemes is that the surveys only cover a limited area (such as the dumping areas) and are not properly extended in the cross- and longshore directions. Consequently, a confident assessment of the impact of the project and the design efficiency may be compromised (Hamm et al., 2002). Overall in Europe, the best monitoring practices are still those adopted in Dutch and German projects, which support regular monitoring activities (Hanson et al., 2002; Schipper et al., 2016; Blossier et al., 2017). Apart from that, although the monitoring may be obligatory, beach nourishments in Europe are usually monitored during their early development, commonly one complete seasonal cycle, corresponding to the time that beach profile needs to reach a new equilibrium state (Larson et al., 1999), and then once or twice a year (Hanson et al., 2002; Yates et al., 2009; Utizi et al., 2016). Dean (2002) suggested a time interval between surveys of 1/2 year to 2 years, unless unusual behavior is expected. In USA, monitoring programs established to track the evolution of nourishment projects are typically undertaken over a few years, but on an annual to biannual basis, with few reports of monthly or seasonal variability (Bodge et al., 1993; Browder and Dean, 2000; Yates et al., 2009). Compared to Europe and USA, the estimated number of nourishment projects including monitoring programs in Australia is much smaller (Cooke et al., 2012).

In Portugal, coastal waters and beaches are considered maritime public domain and are state-owned. The actual policy for safety assessment and erosion control is established by the Ministry of the Sea , which follows the Portuguese Environment Agency (APA) recommendations. The general practice is that there is no funding from private organizations for coastal protection. Thus, all costs are borne by the national government. The APA is responsible for issuing permits (designated through the Environment Impact Statements (DIA) - valid for two years) for coastal protection and other structures in the coastal zones, requiring anticipated studies of possible environmental related-impacts to the project proposal. Although a monitoring scheme is built into this legal structure and described in the DIA, due to the limited public financial resources generally devoted to coastal defense protection, regular monitoring of the coastline is usually neglected. Despite the coastal management strategies still focus on a remedial rather than preventive policies, an overall long-term strategy for coastal management along the coast has been developed, anticipating follow-up programs. In accordance with many countries in Europe (Roberts and Wang, 2012; Burcharth et al., 2015), a general transfer from hard to soft coastal erosion mitigation strategies is emerging, where beach nourishment assumes a central role (RGTL, 2014).

The primary objective of this study was to examine the suitability of a dataset established by DIA in connection to a monitoring program developed for a Portuguese coastal stretch, regularly nourished with dredged material from maintenance activities of the Aveiro Harbor navigation channel, northwestern of Portugal. Attention is given to the beach morphology variability and sediment transport processes by examining temporal and spatial patterns of the nourished beaches and how they change (with focus on cross-shore profile and dumping area evolution). Time series of field measurements collected in connection to underwater nourishment operations performed along Barra-Vagueira coastal stretch were used and analyzed to investigate fill responses in medium-to long-term periods. This dataset encompasses topo-hydrographic surveys collected for 12 cross-sections (1 km spacing) located along the study area (between Sep-2009 and Feb-2015), as well as hydrographic surveys collected within the dumping areas (between Sep-2009 and Apr-2015). Geographic Information System (GIS) techniques and Empirical orthogonal functions (EOFs) were employed as the main tools to relate morphological changes, evolution trends, sediment budgets, sediment transport gradients, and short- and medium-term responses of the fills to the incoming wave conditions. The results from the present paper encourage more frequent monitoring work, especially in cases of beaches with strong seasonal cycles.

2. Field site

Barra-Vagueira is a 10 km long coastal stretch, located on the northwest coast of Portugal, just south of the Aveiro Harbor (see Fig. 1). This stretch, approximately centered on the sandy coast between Espinho and Cabo-Mondego, is currently facing serious erosion problems. The proximity to the Aveiro lagoon and urban areas, the low-lying sandy topography, and the fragile dune system, susceptible to overtopping and flooding during energetic wave conditions and large tidal amplitudes, make this coastal stretch a vulnerable and exposed area to erosion (Coelho et al., 2011; Pereira et al., 2013). As a result, there is an imminent risk of breaching of the dune system that separates the Aveiro lagoon from the sea.

The serious erosion recorded is mainly related to sediment supply deficit, which is resulting from the progressive weakening of the alluvial sources and the sediment blockage by manmade structures (Coelho, 2005; Coelho et al., 2009a; Pereira et al., 2013). The 1.8 million m^3/year of sediment that under normal conditions would come from Douro River (near Porto) and feed the littoral drift towards south (estimated to be 1.5–2.0 million m^3/year), has been decreased to about 0.25 million m^3/year mainly due to the construction of hydro-power dams (Veloso-Gomes, 1991; Bettencourt, 1997; Andrade and Freitas, 2002; Coelho et al., 2009a, 2009b; Costa and Coelho, 2013).

In terms of sediment dynamics, since the longshore sediment transport is interrupted by the Aveiro Harbor breakwaters, strong accumulation of sand is occurring on the updrift (north) side, while a significant retreat of the shoreline occurs at the southern beaches (Barra, Costa Nova and Vagueira). This retreat is controlled by a groin field and a seawall along Costa Nova beach, and a seawall and a groin along Vagueira beach (Fig. 1). According to the long-term shoreline evolution study developed by Veloso-Gomes et al. (2006), for a period of 10 years (1980–1990), the shoreline retreat rate in Costa Nova beach and Vagueira beach is estimated to be 3.7 and 3.9 m/year, respectively. The erosion rates vary over time: for the period 1996–2001, EUROSION (2006) indicates an erosion rate north of Costa Nova and Vagueira of around 6.6 m/year, while the Vagueira waterfront experienced a rate about 7.1 m/year; going back further in time, EUROSION (2006) refers an erosion rate at Aveiro of about 8.2 m/year when analyzing the shoreline movement between 1947 and 1958.

The beach profiles possess dominant seasonal variations and present intermediate to dissipative general morphodynamic behavior north of Aveiro Harbor and intermediate morphodynamic behavior south (SNIRL, 2015). Mean sediment grain sizes along Barra-Vagueira coastal stretch range from medium to coarse sand in the subaerial part of the profile and medium to fine sand in the subaqueous portion. A study

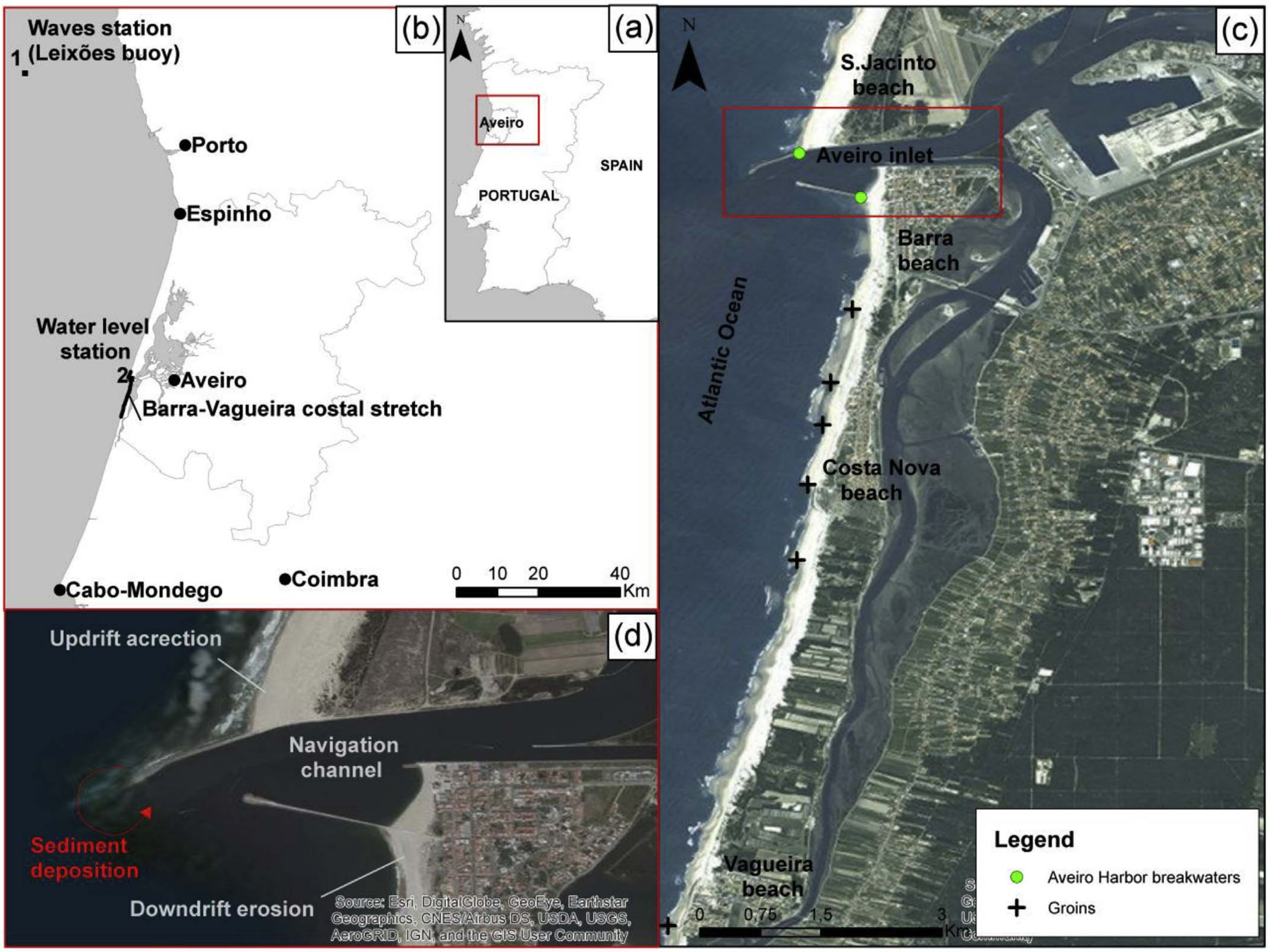


Fig. 1. Location of study site: (a) Portugal; (b) Aveiro district; (c) Barra-Vagueira coastal stretch; (d) Aveiro Harbor-navigation channel (zoom in).

performed by Narra et al. (2015), involving 165 sediment samples collected at 5 different locations, along 3 cross-shore profiles over 8 months, in Barra beach, indicated that the dune base and the upper foreshore limit at high tide can have a d_{50} ranging from 0.2 to 0.4 mm and 0.3 mm to 1.7 mm, respectively. Narra et al. (2015) also concluded that the variability in the median grain size of the sediments found in higher levels of the profile, is smaller than in deeper (underwater) areas.

2.1. Dredging/dumping operations and related harbours activities

In order to control beach erosion along the Barra-Vagueira coastal stretch and to improve the navigation channel conditions at Barra inlet, two major projects were undertaken by the Aveiro Harbor Administration – AHA (beyond the regular activities of navigation channel maintenance) between 2009 and 2015: “Dredging of Barra with reinforcement of the dune system” (AHA, 2009) and “Re-configuration of Barra north breakwater” (AHA, 2013). During this time period (2009–2015) regular surveys of cross-shore beach profiles and the bathymetry of the dumping areas were undertaken and made available by AHA, which allowed for the monitoring of impacts related to the interventions.

The main objective of the first project was to dredge 1 million m^3 of sand (performed during two time periods, see Table 1) from the bottom of the inlet entrance of the Aveiro Harbor and to use the obtained sand to reinforce the littoral system in the Costa Nova beach. The second major project conducted by AHA aimed at extending the north breakwater by 200 m, considering a new realignment of the navigation channel, carrying out dredging works to ensure safe navigation at a bed level of −12.5 m (Chart Datum, CD). The relationship between CD and

Table 1
Details of the dredging/dumping operations performed during 2009–2015 (AHA, 2012 and 2013).

Date of dredging/dumping		Source of the borrow material	Location	Volumes (m^3)
Year	Month			
2009	April/May	Navigation channel	DA2	500 000
	September/ October	Navigation channel	DA2	500 000
2012	June	Breakwater construction	DA1	169 200
2013	May	Breakwater construction	DA2	66 700
	May	Navigation channel	DA1	79 100
	July	Navigation channel	DA1	251 700
	July	Navigation channel	DA2	1 008 100
	October	Navigation channel	DA2	97 700
	November	Navigation channel	DA2	101 600
2014	September	Navigation channel	DA2	64 800
	October	Navigation channel	DA2	110 600
	November	Navigation channel	DA2	148 300
	December	Navigation channel	DA2	208 200
2015	May	Navigation channel	DA2	137 800
	November	Navigation channel	DA2	188 300
	December	Navigation channel	DA2	106 400

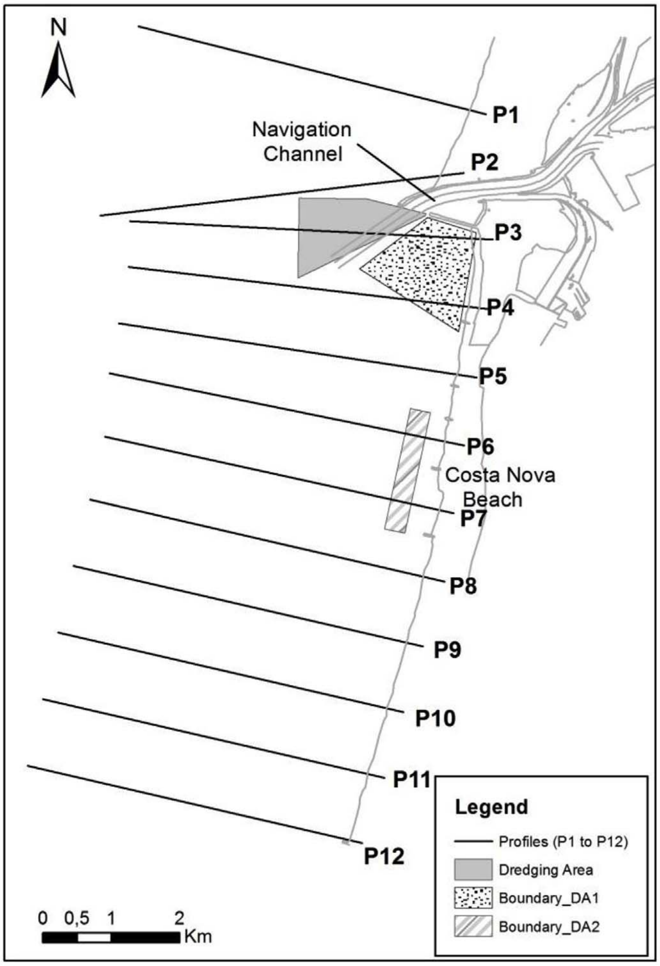


Fig. 2. Location plan of the dredging and deposition areas and surveyed cross-sections.

Mean Sea Level (MSL) at Aveiro is given as MSL = CD + 2 m.

Table 1 summarizes the information related to the dredging and dumping operations carried out at Barra and Costa Nova beaches during 2009–2015. Some of the information described, related to the dates and volumes, was put together based on the interpretation of the design drawings and survey files made available by AHA in connection with the major projects undertaken.

The dredged material resulting from the channel and breakwater extension was deposited in the subaqueous part of the beach profile at two main sites. The first site (DA1) was limited by the south breakwater and the 1st groin of Costa Nova beach (2012–2013), between bed levels −4 and −7 m (CD). The second site (DA2) was bounded by the 3rd and the 5th groins of Costa Nova (counting from north to south, Fig. 2), between bed levels −2 and −5 m (CD).

Since the borrow material was obtained mostly from the navigation channel and dumped in the subaqueous portion of the profile, the median grain size of the nourished sand placed in the Barra and Costa Nova beaches is considered similar to the native sediments (medium to fine sand). Besides the dredging and deposition operations detailed in Table 1, in 2014 the Barra-Vagueira coastal stretch was also nourished in the subaerial portion of the beach. The borrow material was moved from dredged sand deposits close to Aveiro Harbor (located 4 km from the fill spot) with trucks. Dredging operations detailed for 2015 were not included in the present study.

2.2. Wave climate

In general, the Portuguese west coast, which includes the coastal region of Aveiro, is heavily exposed to waves generated in the North Atlantic. Waves coming from the NW quadrant are the most frequent, occurring during about 80% of the year. The mean significant wave height is around 2–3 m, while the mean period is between 8 and 12 s. The tide regime is semi-diurnal, with an amplitude range between 2 m, during neap tides, and almost 4 m, during spring tides (Coelho, 2005; Coelho et al., 2009b; Pereira and Coelho, 2013). During storms, especially common in winter, offshore significant wave heights, coming predominantly from northwest, may reach 8 m and persist for up to 5 days (Pires, 1989; Coelho, 2005; Coelho et al., 2009b). Moreover, storm surges resulting from the influence of low-pressure systems can be frequent, but reaching 1 meter at the most (Coelho, 2005).

The wave regime at the Portuguese NW coast is obtained from data recorded at Leixões buoy, operated by the Portuguese Hydrographic Institute (IH). This buoy is located 78 km NNW from Aveiro, at a depth of 83 meters (Fig. 1). Wave data records from the Leixões wave buoy are considered to be representative for the offshore wave conditions at the study site (Narra et al., 2015). Thus, time series of peak period (T_p) and associated wave direction (θ), significant wave height (H_s), and average period corresponding to H_s (T_{Hs}), at 3-hour intervals (normal data acquisition) and 30-minute intervals (storm data acquisition) were analyzed for the period corresponding to the field monitoring campaigns (Sep-09/Apr-15). In the analysis, it was assumed that records with significant wave height greater than 5 meters correspond to storm conditions. If the interruption between storm records was greater than a tidal cycle it was considered as a division between storms and for 10 or more storm records existing during a period equal or greater than 8 h, the storm was considered long (persistent). Fig. 3 displays the distribution of the wave directions and wave heights for normal and persistent storm conditions, respectively, for the period between Sep-09 and Apr-15.

Overall, time series of 3-hour records showed a maximum and average significant wave height of 8.89 m and 2.06 m, respectively, whereas the maximum wave peak period was around 18 s, with an average value of 11.05 s. Waves come mostly from the NW sector (46% of the observations) followed by the WNW (29%) and NNW (11%) directions. Regarding persistent storm conditions, a maximum and average value for H_s of 9.21 and 4.80 m, respectively, were observed. The peak period reached an average value of 14.34 s and the NW and WNW sectors were the most representative, corresponding to 90% of the observations (significant increase of the WNW quadrant to 37%).

Seasonal variations indicate that waves coming from the SW quadrant are infrequent in summer and occur mainly during winter and transition periods (summer-winter and winter-summer). In winter, the waves are more oriented towards the south (see Fig. 3b), presenting a wide distribution of directions, whereas during the summer the wave climate is more typical with higher percentages of waves coming from NW. Fig. 4 summarizes the average and maximum value of H_s as well as the predominant wave direction sector for each month between Sep-09 and Apr-15.

Major storms (identified by the number of storm records for each month) hit the study area in Jan-13, Dec-13, Jan/Feb-14, Nov-14 and Jan-15. Most energetic winter conditions occurred between Dec-13 and Mar-14, registering average and maximum values for H_s of about 3.38 m and 8.89 m, respectively. During these energetic storms severe damage and beach erosion were reported by the media for the study site.

2.3. Monitoring program

Since 2009, a monitoring program has been conducted by the Aveiro Harbor Administration in connection with the dredging and dumping operations carried out at Barra and Costa Nova beaches. The monitoring campaigns encompassed beach profile measurements and bathymetric surveys covering the dumping areas. Profile surveying using a multi-beam echo-sounder (transducer of 200 khz and accuracy

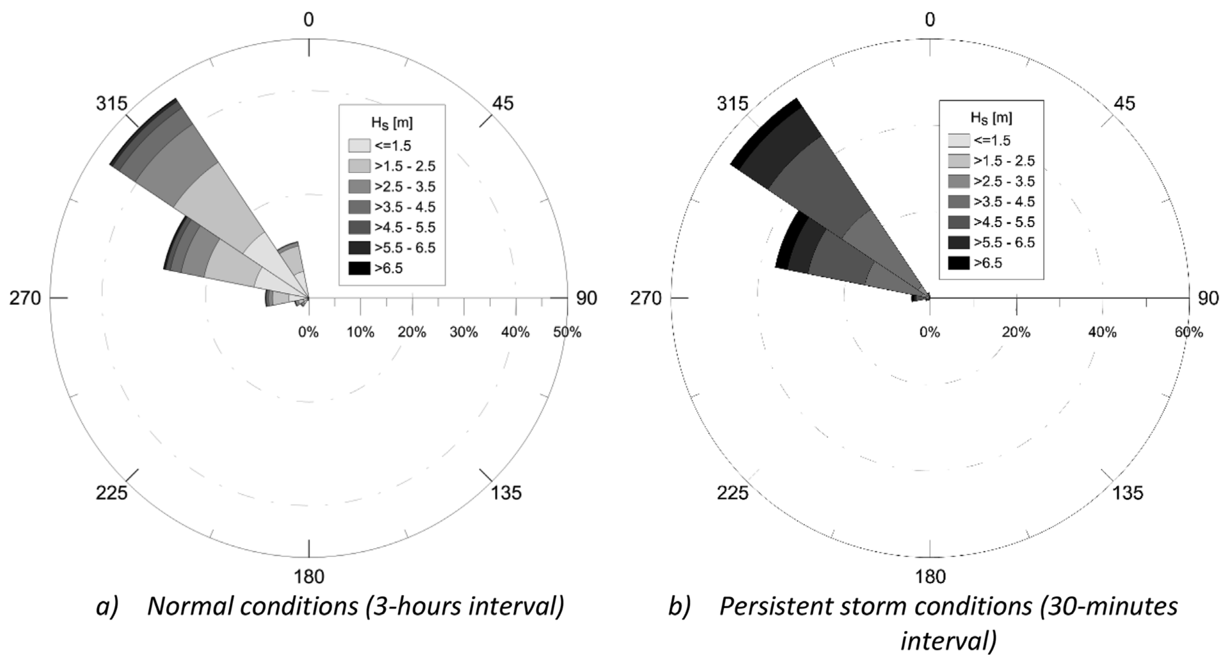


Fig. 3. Wave rose with energy based on significant wave height, H_s, measured at Leixões (2009–2015).

of 0.01m ± 0.1% water depth) and a Real-Time Kinematic (RTK) global positioning system (GPS Leica GC15 RTK – with coordinate system transformation to local Datum 73) started in Sep-09, just before the second fill placement (Sep/Oct-09, Table 1), and continued until Feb-15, with approximately 1 year frequency between surveys. In total, 12 cross-sections (P1-P12) were surveyed with a spatial resolution of 1 km between survey lines from the updrift side of Aveiro Harbor (S. Jacinto beach) to Vagueira beach (see Fig. 2); 2 lines were located at north of the Barra inlet (P1-P2; accreting beach) and 10 lines were located at south of the harbor covering the Barra-Vagueira coastal stretch (P3-P12; eroding beach). From these 10 profiles, two of them are located between the southern breakwater and the 1st groin of Costa Nova (P3 and P4), one profile between the 1st and the 2nd groin (P5), the 3rd and the 4th groin (P6) and the 4th and the 5th groin (P7). The remaining eroding profiles are located southward of the 5th groin of Costa Nova. Each profile was surveyed from an alongshore base line located close to the top of the dune (backshore region) to a bed level −11 m (CD) or more. In addition, using a multibeam echo-sounder (transducer of 250 kHz, decimeter accuracy) bathymetric surveys were collected for the dumping areas annually, just before and after the fill material was placed, spanning a total period of almost 6 years (Sep-09/Apr-15). Dates and locations of the surveys are detailed in Fig. 5.

The temporal resolution of the surveys implies some limitations as to what the data can provide regarding analysis and model application. Due to lack of data covering the detailed beach response to seasonal or storm wave conditions, they are not appropriate for analyzing coastal evolution induced by variable forcing conditions. Instead, the present study focuses on the general evolution pattern at the inter-annual scale and the related sediment transport at the study site.

3. Analysis methods

The set of data collected in the field was employed to study the morphodynamic evolution of Barra-Vagueira coastal stretch between

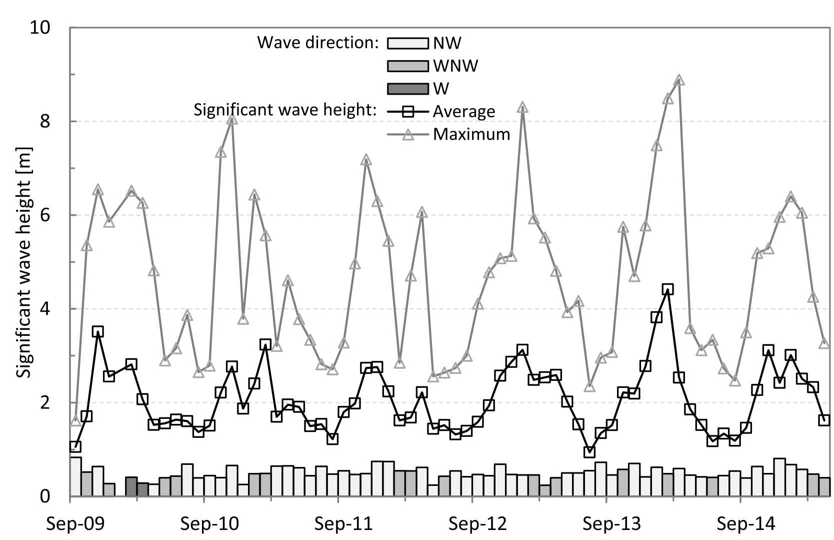


Fig. 4. Monthly significant wave height and respective dominant sector (bars are in the scale 0–1 representing the percentage of wave occurrence).

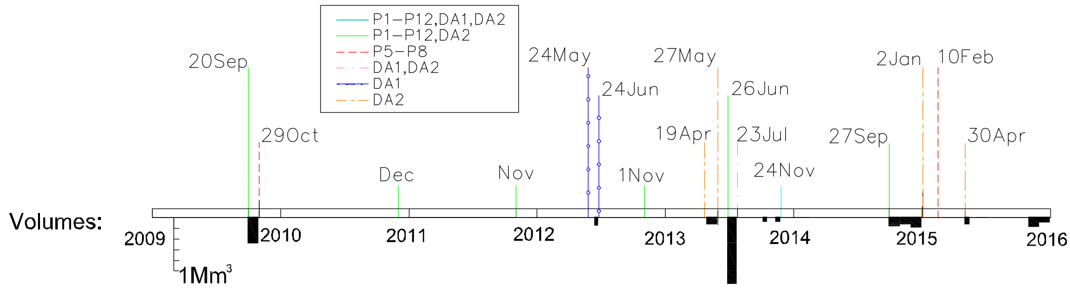


Fig. 5. Timeline of the surveys performed at the study (monitoring campaigns) and filling volumes.

2009 and 2015. First, cross-shore profile variability is discussed, followed by the general evolution of the dumping areas through the use of GIS techniques and EOFs. Morphologic changes, evolution trends, sediment budgets, and fill responses in a short-to long-term perspective within the dumping areas are analyzed.

3.1. Cross-shore profile analysis

The understanding of the characteristic scales in time and space of the beach profile behavior has direct applications in coastal engineering projects, including beach nourishment design and the siting of coastal structures (Larson and Kraus, 1994). However, frequently limited information is available regarding depth change along the profile and its time variation. For S. Jacinto-Vagueira coastal stretch, profile data are available from Sep-09 to Feb-15 and are here used to characterize the beach profile evolution following the implementation of the nourishments. Although the quantification of beach change was limited by data constraints linked to the temporal and spatial resolution, behavior patterns could be distinguished through the analysis of a number of striking differences and similarities in the beach topo-hydrography, observed in the *in situ* surveys. Temporal profile variability was first examined for a general understanding of the spatial and temporal scales of the recorded beach profile change. Then, individual morphological features related to the beach shape, such as dune, shoreline position, longshore bars, and nourishment schemes were analyzed. The shoreline position was set as the MSL (approximately the pivot point of seasonal variations) and its evolution was evaluated based on the field observations. The cross-shore position of the sandbar, here defined as the total distance from the instantaneous shoreline to the bar crest, and the bar volume per unit longshore length (m^3/m) were also quantified. Nourishment migration is discussed based on profile observations together with design specifications.

To estimate cross-shore volumetric changes a common range for each surveyed profile was established (see Fig. 6c). This common range comprises the data region covered by the available surveys. The MSL was selected as the reference elevation to separate the subaerial and subaqueous portions of the beach and sand volumes were calculated per unit longshore length (m^3/m) in relation to the first survey (Sep-09). Fig. 6 displays the surveyed profiles for four transects representative of the updrift region (P2), dredged and nourished areas (P3 and P7, respectively) and the southern stretch (P9).

3.2. Bathymetric analysis

To investigate the morphological response of the dumping areas, a database georeferenced in a GIS (*ArcGis* software) was created from the hydrographic surveys collected by AHA annually, just before and after nourishment operations (Fig. 7). *ArcGis* tools were applied to determine elevation differences and sediment budgets between surveys. Field data related to the both nourishment areas were processed individually.

Through the use of '*Raster Interpolation*' tool by *3D Spatial Analyst* extension of the *ArcGis* software, the inverse distance weighting (IDW) method was applied to generate digital elevation models. Since the bathymetric data sets resulting from distinct monitoring campaigns covered different zones, three main areas of analysis, hereafter referred to as the common areas (CA), were defined based on the intersection of the surveyed areas. The first one (CA1), with 0.43 km^2, corresponds to DA1 and is alongshore bounded by the south breakwater of Barra and the 1st groin of Costa Nova, extending between the water depths 2.5 and 8.5 m (see Fig. 7a). For DA2, four surveys were identified as presenting short extension and thus, two main common areas (CA2A and CA2B) were established for analysis: one resulting from the intersection of all surveyed areas, with exception of the survey of Jan-14 (which presents the minor area coverage), and another one excluding surveys of Dec-10, Nov-11, Nov-13, and Jan-14. Thus, the second (CA2A) and the third (CA2B) common area (see Fig. 7b and c), with 0.53 and 1.05 km^2, respectively, correspond to DA2 and are both limited by the 3rd and the 5th groin of Costa Nova. In the cross-shore direction, CA2A is limited by the water depths 2 and 9 m (CD), whereas CA2B extends to deeper levels around −10 m (CD). The reference bathymetry was taken to be May-12 for DA1 and Sep-09 for DA2, each one corresponding to the first survey that was carried out in each area (Fig. 7).

For each defined common area, sediment volume variations were estimated using a *Functional Surface* tool (*'Surface Volume'*). Elevation differences between survey pairs were obtained with the *Spatial Analyst tool 'Minus'*, subtracting the interpolated values of two input raster's on a cell-by-cell basis. In cases, where the altimetric comparisons could be extended behind the boundaries of the common areas, enabling a better assessment of the morphological changes of the fills, sediment budgets were also estimated. Surveys carried out just before and after the fill placement were used to evaluate the short-term behavior of the fills, whereas surveys more separated in time were used to investigate the medium/long-term response of the fills (see Table 2).

3.3. EOF analysis

EOFs were employed as an attempt to examine spatial and temporal variations of the beach profile shape close to DA2 (Costa Nova beach) on a short- and long-term basis. Topo-hydrographic data for four cross-shore profiles (P5 to P8), collected during eight surveys from 29-Oct-09 to 15-Feb-15, were used as input data to the EOF analysis. Linear interpolation was employed to obtain elevations at the same cross-shore locations for all surveys taken at a particular transect. Thus, an input data matrix *D(z,t)* was constructed, containing rows of elevations surveyed, *z*, at specific dates, *t*, in columns. Although the dune behavior could not be described completely by data variation, elevation contours between the seaward dune face (8 m to chart datum) and the depth of closure constituted a good coverage by the surveys.

4. Results

The first part of the analysis focuses on the cross-shore variability of the beach profiles, describing morphological changes linked to dune evolution, shoreline position, bar system, and nourishment behavior, as well as examining volumetric changes (m^3/m of shoreline) for the subaerial and subaqueous portion of the cross-shore profiles (section

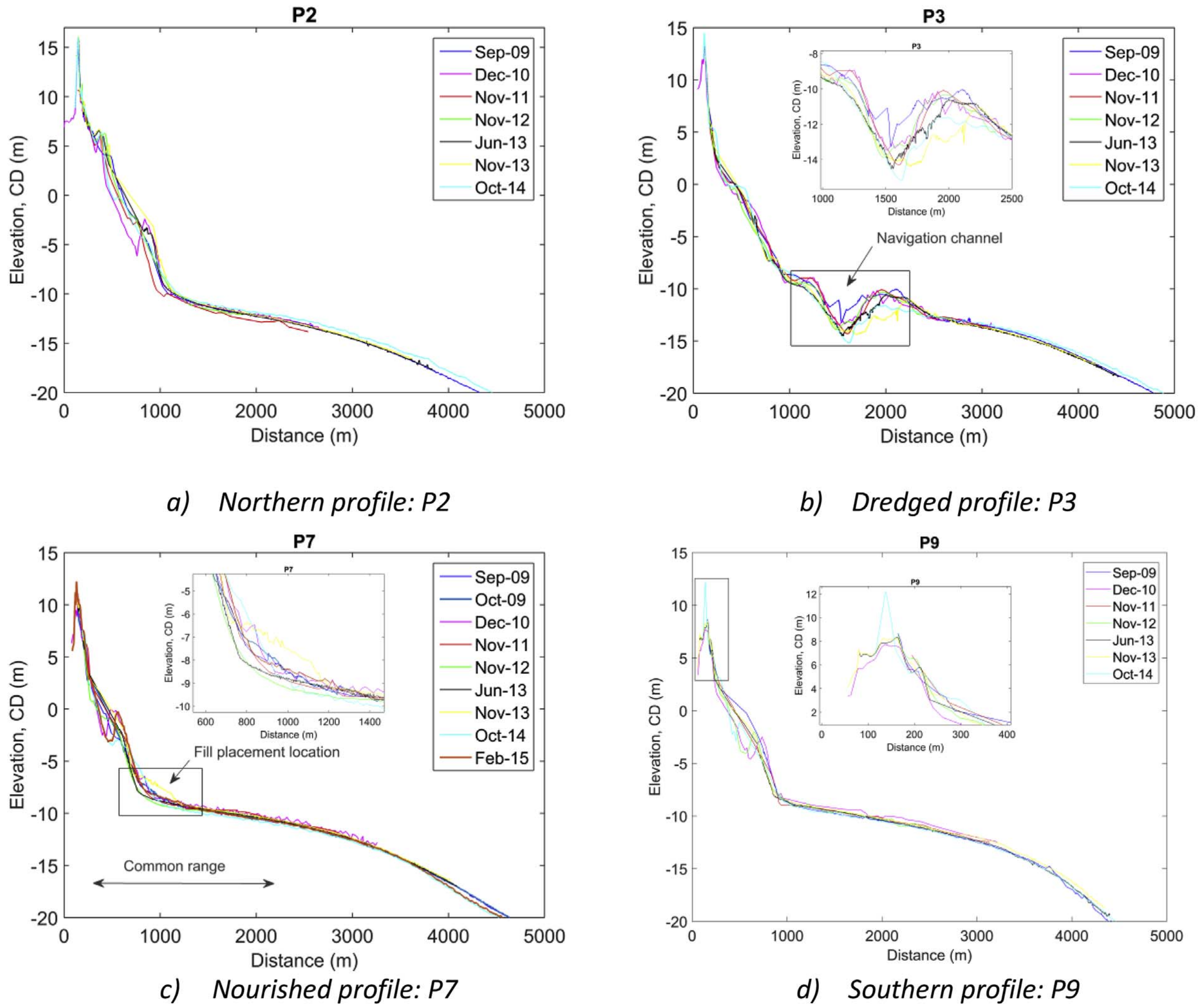


Fig. 6. Surveyed cross-shore profiles for representative transects of the updrift region (P2), dredged and nourished areas (P3 and P7, respectively) and southern region (P9).

4.1). Additional analysis involves the bathymetric surveys targeting the dumping areas and their evolution at two main time scales: short-term and medium/long-term responses of the beach fills (section 4.2). Finally, results from the application of a multivariate statistical method (EOF) to the survey data covering DA2 are presented and discussed (section 4.3).

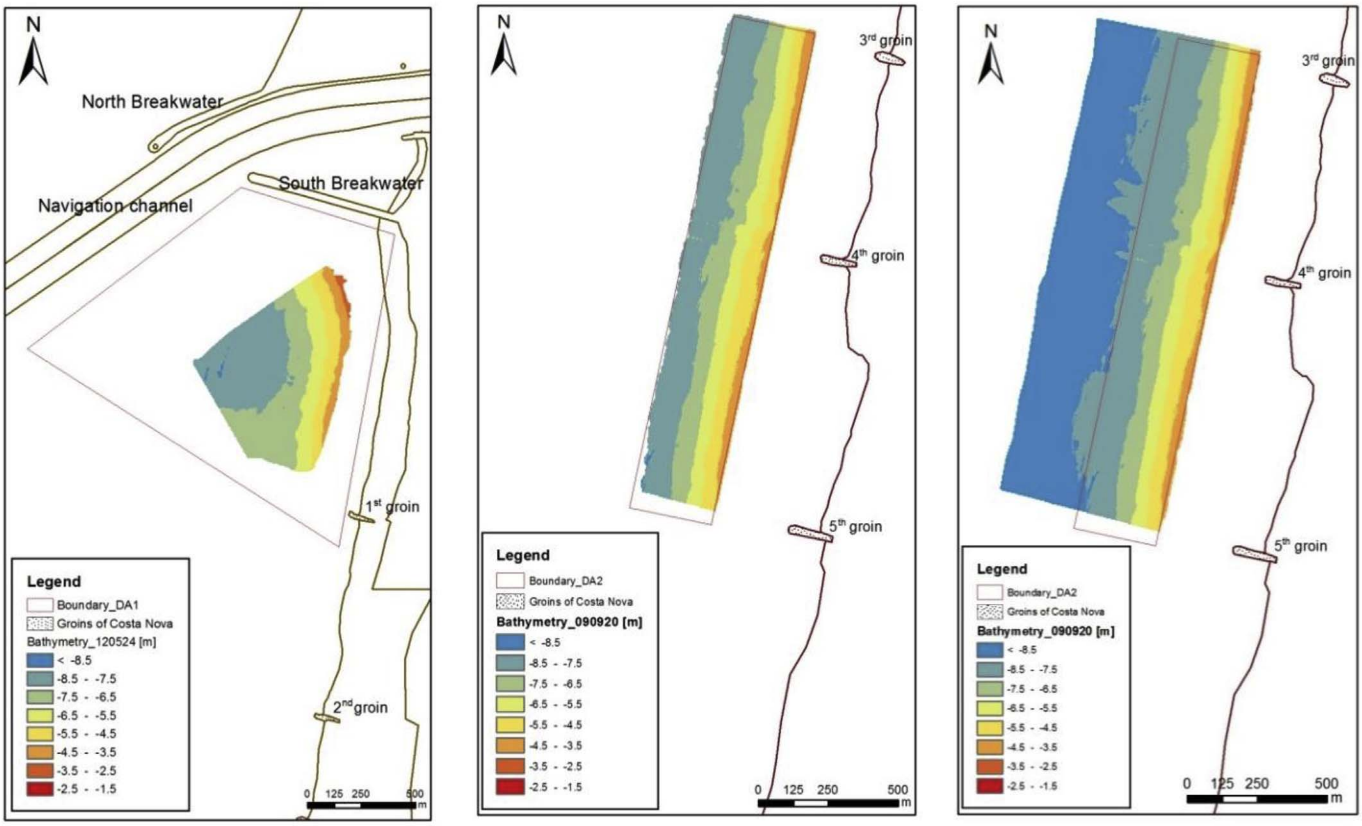
4.1. Cross-shore profile variability

4.1.1. General behavior

Maximum variability in elevation of the beach profile is generally obtained between the high water level (+4.0 m CD) and the breaker zone limit (shallow part of the study site). Offshore of this area, changes in profile depth decrease, presenting its minimum around −13 m (CD) elevation contour (Hallermeier, 1978; Birkemeier, 1985; Coelho, 2005). This depth is in agreement with the values discussed in the literature for the depth of closure, where the cross-shore seaward sediment exchange is negligible from an engineering perspective (Coelho, 2005). Landward, where the largest depth variations are observed, changes in profile shape refer mostly to the seasonal variations resulting from processes controlling the erosion and recovery of the dune and berm (see Fig. 8).

The northern profiles (P1-P4) show a slight increase in profile bed elevation for deeper areas than −13 m (CD) elevation contour, possibly related to the extension of the northern breakwater, promoting sand accretion for deeper waters on the updrift side of Aveiro Harbor and in its protected downdrift area (see Fig. 6a). The opposite pattern prevails for the most southern profiles (P5-P12). The variability exhibited by the profiles located just south of the Aveiro Harbor (P3-P4) seems to be affected by the maintenance operations and natural recovery process of the navigation channel (P3, see Fig. 6b), together with the diffraction currents generated by the Aveiro Harbor breakwaters (P4) and the presence of a nearshore sand shoal (intercepted by P4). Profile P5 shows a particular response, where the measured evolution in time displays significant morphological changes in the subaqueous portion of the profile after 2013. These changes suggest that a large amount of sand in the area defined by the depths −7 and −10 m (CD) moved in the onshore direction forming a nearshore sandbar. Observations from Feb-15, indicate that this sandbar has been driven towards the beach, showing a landward migration of its crest of around 144 m with respect to the Oct-14 survey. In general, the largest variations in the profile shape registered for the southern profiles (P6-P12) are mostly related to seasonal variations.

In Sep-14 and Feb-15, field observations indicated that, in the downdrift area of DA2, neighboring profiles exhibited similar variations in the dune region, revealing an average increase in the dune crest (see Fig. 6d). This dune growth pattern, recognized south of DA2 along approximately 2 km of Costa Nova beach (intercepting profiles P8 and P9) contributed to the reinforcement of the backshore region of the Costa Nova beach.



a) 24-May-12, CA1 b) 20-Sep-09, CA2A c) 20-Sep-09, CA2B

Area=0.43 km^2 Area=0.53 km^2 Area=1.05 km^2

Fig. 7. Common areas of the bathymetry surveys, for dumping areas DA1 (CA1) and DA2 (CA2A and CA2B).

Table 2
Bathymetric comparisons undertaken for each surveyed dumping area.

Area	Analysis	Comparisons	Duration
DA1	Short-term behavior	May-12 to Jun-12	One month
		Jun-13 to Jul-13	One month
	Medium-term behavior	Jun-12 to Jun-13	Twelve months
		Jul-13 to Nov-13	Five months
DA2	Short-term behavior	Sep-09 to Oct-09	One month
		Apr-13 to May-13	One month
		May-13 to Jun-13	One month
		Jun-13 to Jul-13	One month
	Medium-term behavior	Oct-09 to Dec-10	Fourteen months
		Oct-09 to Nov-11	Twenty-five months
		Oct-09 to Oct-12	Thirty-six months
		Oct-09 to Apr-13	Forty-two months
		Jul-13 to Nov-13	Four months
		Jul-13 to Sep-14	Ten months
		Sep-14 to Apr-15	Seven months

4.1.2. Shoreline position and offshore bar system evolution

Fig. 9 presents the variation in shoreline position with time based on the 12 surveyed cross-sections. As expected, the coastal area along P5-P7 appears to be the region with least retreat in the shoreline position over approximately 5½ years of monitoring, denoting coastline advance mainly after low-energy and nourishment periods. During the storms of Oct/Nov-10, the beach was severely eroded along the entire coastal stretch, resulting in a significant decrease of the beach width observed on Dec-10. The opposite behavior is recorded in Nov-11 and Jun-13 yielding a general advance of the shoreline in relation to the Dec-10 survey. The most seaward shoreline position is observed in Nov-13 along P3-P7, possibly as a response to the fill material dumped in the summer of 2013 in connection with the construction of the northern breakwater. Again, in Oct-14 a general retreat of the shoreline occurs (relative to Nov-13), being an exception to this pattern the profiles located south of DA2 (P9-P11).

Fig. 10 displays sandbar volume and distance to bar crest from the shoreline (defined at MSL) for each transect. Overall, profiling has indicated a more frequent presence of the bar southward of P7 compared to the updrift side, where the Aveiro harbor breakwaters and the groin system (located at Costa Nova) are physically affecting the natural flow of the sediment transport and consequently the potential for cross-shore material exchange. The inverse response is observed for the shoreline position evolution: bar appearance (or net onshore bar migration) connected to a shoreline retreat and vice-versa (see Figs. 9 and 10).

In 2010, the presence of a quasi-uniform longshore bar can be clearly identified at an average distance of 346 m from the shoreline, and a sand volume ranging from 266 to 859 m^3/m. As the surveying was carried out during the winter and preceded by two months of high-energy waves (see Fig. 4), a shift towards a more frequent recurrence of breaking conditions or more intense breaking promoting a larger offshore sediment transport has contributed to this bar appearance. The seasonal change in the wave height, promoting a larger seaward sediment movement, is thus hypothesised to be the main responsible process for the generalized shoreline position retreat registered in the same period (Fig. 9). This generalized phenomenon (bar appearance) for almost the whole stretch exalts that this phenomenon is an intermittent process confined to high-energy periods.

The highest sandbar volume was recorded to be about 1016 m^3/m, for P8 in Feb-15, with an average crest position located 311 m from the shoreline. This large value is partially attributed to the southern

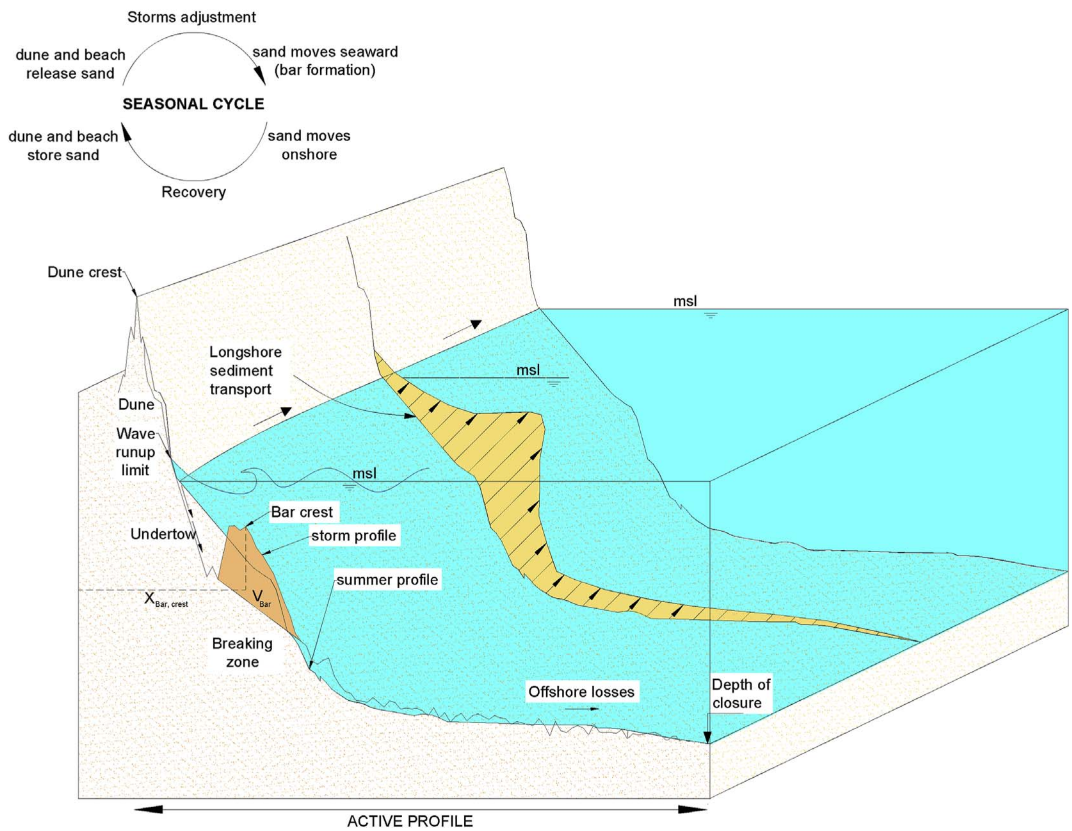


Fig. 8. Scheme of morphological changes to the beach profile during a seasonal cycle. Definition sketch of bar properties: bar crest, bar volume (V_{Bar}) and bar crest distance to the shoreline ($X_{Bar,crest}$).

spreading of the sand dumped at DA2, which may have helped to feed the bar.

4.1.3. *Nourishment evolution*

Regarding the nearshore nourishment material, only the signal from the large fills carried out at DA2 in Sep/Oct-09 and in Jul-13, could be clearly recognized in the profile data. The absence of detailed topo-hydrographic surveys immediately before and after the generality of the fills prevented the study of the initial process of fill adjustment. However, even without adequate survey frequency, significant changes in profile elevation could be distinguished for P6 and P7 between −6 and −10 m (CD) contours. These changes can be directly linked to the effect of the fills placed in Sep/Oct-09 and in Jun-13, although some cross-shore displacement to offshore is observed in the data (in response to the wave climate). In spite of the lack of frequent data, considering the project specifications for the dumping operations (between −2 m and −7 m CD) and the performed surveys, it was possible to conclude that the large fill material interventions experienced seaward transport, carrying the nourished material to areas offshore of the dumping boundary.

4.1.4. *Subaerial and subaqueous cross-shore volumetric changes*

Fig. 11 shows the cumulative volumetric changes between Sep-09 and Feb-15 for the entire coastal stretch under monitoring (S. Jacinto-Vagueira, P1-P12). The results below highlight the strong sediment dynamics that take place in the subaqueous portion of the profile: 9 times higher maximum variability compared to the subaerial region. Nevertheless, as the cross-shore width of the subaqueous portion of the profile is much wider than the subaerial, normalized volumes per cross-shore length, $m^3/m/m$, evidenced a higher average of sediment transport distribution occurring in the upper part of the profile, although its total significance is lower than the subaqueous response. The observations stress the importance of surf-zone hydrodynamics over the time scale studied here that largely shape this coastal system.

Fig. 11a displays the subaerial volumetric change, indicating a general sand increase north (P1-P2) and immediately south (P3) of the Aveiro Harbor and within DA2 (P7-P8). Erosion is noted for P4 and P5, while a stable or slightly eroding area is observed along P9-P11, with P10 being the section that shows the lowest volume variability (maximum value of −90 m^3/m obtained in 2010). In Dec-10, the beach was in a typical winter state, implying a significant decrease in subaerial sand volume almost everywhere along the coast (except in the neighboring areas of P4 and P7). In general, the beach width was narrow (see Fig. 9) after large amounts of sand were moved from the dune and the berm to form a longshore bar (see Fig. 10). In Nov-11, due to the high percentage of waves coming from SW during Oct-11, an accreted volume is registered in profiles located just south of the harbor (P3 and P4). In the summer of 2013, sediment moved back onshore, contributing to the increase of the subaerial beach volume for half of the profiles studied. Contrary, a general volume decrease is observed in Oct-14 for the majority of the profiles (relative to Nov-13), where the erosion in the subaqueous part of the profile for the most southern stretch (P6-P12) is particularly evident. This spatial erosion pattern is probably related to the major storms that hit the study site during Jan/Feb-14 (see the high values of H_s in Fig. 4). It is estimated that the extremely energetic winter prior to the summer of 2014 was the main cause of the erosion in the surveyed area, leading to an average total sand volume deficit of about 687 m^3/m (sum for the subaerial and subaqueous parts of the profiles).

Below MSL (Fig. 11b), a highly erosional area can be observed between P3-P5. For P3, this erosion is mostly governed by dredging operations of the Aveiro Harbor navigation channel (see Fig. 7b) as the largest variations (losses) took place in deeper areas (below the −10 m CD) just after the major maintenance operations (Sep-09/Dec-10; Jun-13/Nov-13). For P5, on the other hand, the largest loss of sediment has been registered between the first and the second measurements,

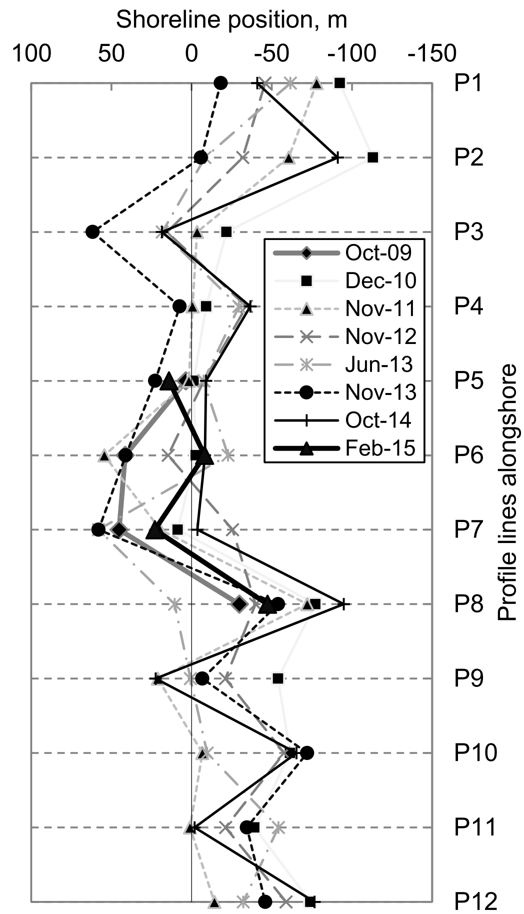


Fig. 9. Shoreline position (MSL) variation relative to Sep-09 shoreline obtained at surveyed profile lines P1 to P12.

covering a period of only one month. Although it was not possible to identify the potential source of this behavior, the first survey (Sep-09) was considered questionable and has been dropped. By analyzing the behavior at this line with reference to Oct-09 (one month later), the profile registered accretion, benefiting from its position between the two dumping areas. Thus, for the following analysis, the reference survey for P5 was considered Oct-09. The nourished profiles (P6 and P7) are benefiting the most from the sediment added during the periods involving fill operations, whereas profile P2 shows an accretionary trend that can be attributed to the Aveiro Harbor breakwater extension (see Figs. 6a and 11b), displaying only a significant volume reduction in Oct-14 (1063 m^3/m). In Jun-13, a general increase of the subaqueous volume of the beach profile is identified for the entire study site (except in the vicinity of P3). This behavior can be explained by the natural recovery process of the beach (see Fig. 8), inducing onshore sediment movement and contributing to the beach widening (also in accordance with the subaerial changes, see Fig. 11a).

4.2. Evolution of dumping areas

The responses of the beach fills were put in perspective by comparing chronological sand level changes. The bathymetric evolution of the dumping areas were investigated for short- (just after the fills) and medium/long-term scales (months to years after the fills) by analyzing changes in seabed elevation. Fig. 12 displays the sediment balance for the dumping areas as a function of time. Figs. 13 and 14 illustrate examples of the short- and medium/long-term evolution observed for dumping areas DA1 and DA2.

The interpretation of the results is performed considering two main viewpoints: short-term and medium/long-term evolution of the sand nourishment in each dumping area.

4.2.1. Dumping area DA1

Five hydrographic surveys were carried out, and employed in the analysis, between May-12 and Nov-13, in DA1. The results for the common area (CA1) show positive sediment balances during almost all the periods between surveys, the only exception to this pattern being the period between July-13 and Nov-13 (which presents a small loss of 0.02 Mm^3 of sand). To investigate the short-term response of DA1, two bathymetric maps were generated and compared with a time difference between them of one month. The accretion of 0.16 Mm^3 registered between May-12 and Jun-12 is in good agreement with the sand volume dumped in June (169 218 m^3). However, the increase registered between Jun-13 and Jul-13 (0.15 Mm^3) corresponds to only 61% of the nourishment carried out during that period (251 721 m^3), implying that 39% of the dumped material moved out from the surveyed area in one month (Fig. 12).

Two periods addressing the medium-term response of the fills placed in DA1 were analyzed: Jun-12/Jun-13 (1 year) and Jul-13/Nov-13 (five months). The increase of approximately 0.08 Mm^3 registered one year after the first fill agrees with the sediment volume that was dumped in May-13 (79 061 m^3). This indicates that the material dumped in 2012 (first fill) remained within the common area, although analysis of the surveys shows that the dumped sand has moved alongshore (Fig. 13b). The sand was transported mostly to the south, although it was also possible to identify some accretion to the north. This particular transport pattern may be related to diffraction currents generated by the northern Aveiro Harbor breakwater, which can invert the sediment transport direction in its shadow area. An erosion hotspot due to divergence in the sand transport is also identified in Fig. 13. Between Jul-13 and Nov-13 an 8% loss of fill material dumped in Jul-13 was recorded. In general terms, the erosion or accretion associated with DA1 decreases or increases, respectively, if the analyzed area is extended (when allowed by available surveys), indicating that the nourishment material remains in the local area, although outside DA1. Between May-12 and Nov-13, the cumulative sand volume change in DA1 was calculated to be 0.37 Mm^3, corresponding to 74% of the dumped material (Fig. 12).

4.2.2. Dumping area DA2

Thirteen surveys were available and analyzed for dumping area DA2. According to the sediment budgets analysis (Fig. 12), both common areas CA2A and CA2B present consistent behavior, with almost the same trends of erosion/accretion with time. Changes in seabed elevations immediately before and after the nourishment operations (approximately one month) were investigated (see Fig. 14a and c, as examples). The nourishment mound can be identified by the central darker spots (orange) within the dumping area boundaries (DA2). During May/Jun-13 and Jun/Jul-13, there is a clear signal showing a seaward migration of the fill material. The accumulation of sediment obtained for CA2A corresponds only to 67% (Sep/Oct-09) and 53% (Jun/Jul-13) of the sediment accumulation in CA2B, implying that an average of 40% of the dumped material moved out from CA2A in just one month (see Figs. 12 and 14a–14c). Also, approximately 51% of the dumped material “disappeared” from the surveyed area between Jun-13 and Jul-13. Here, uncertainties resulting from surveys errors are estimated to be around ± 105 000 m^3 for CA2B), corresponding to approximately 10% of the fill volume. Two months after the nourishment was carried out in May-13 (66 725 m^3), there is evidence for offshore transport with losses around 0.03 Mm^3 in CA2B (47% of the deposited material).

The results of bathymetric analyses ranging from months to several years for DA2 are displayed in Fig. 14b and d. Until Nov-11, the nourishment eroded (blue) while sand accumulated in the nearshore. The increase of sediment in 2010 is mainly related to seasonal

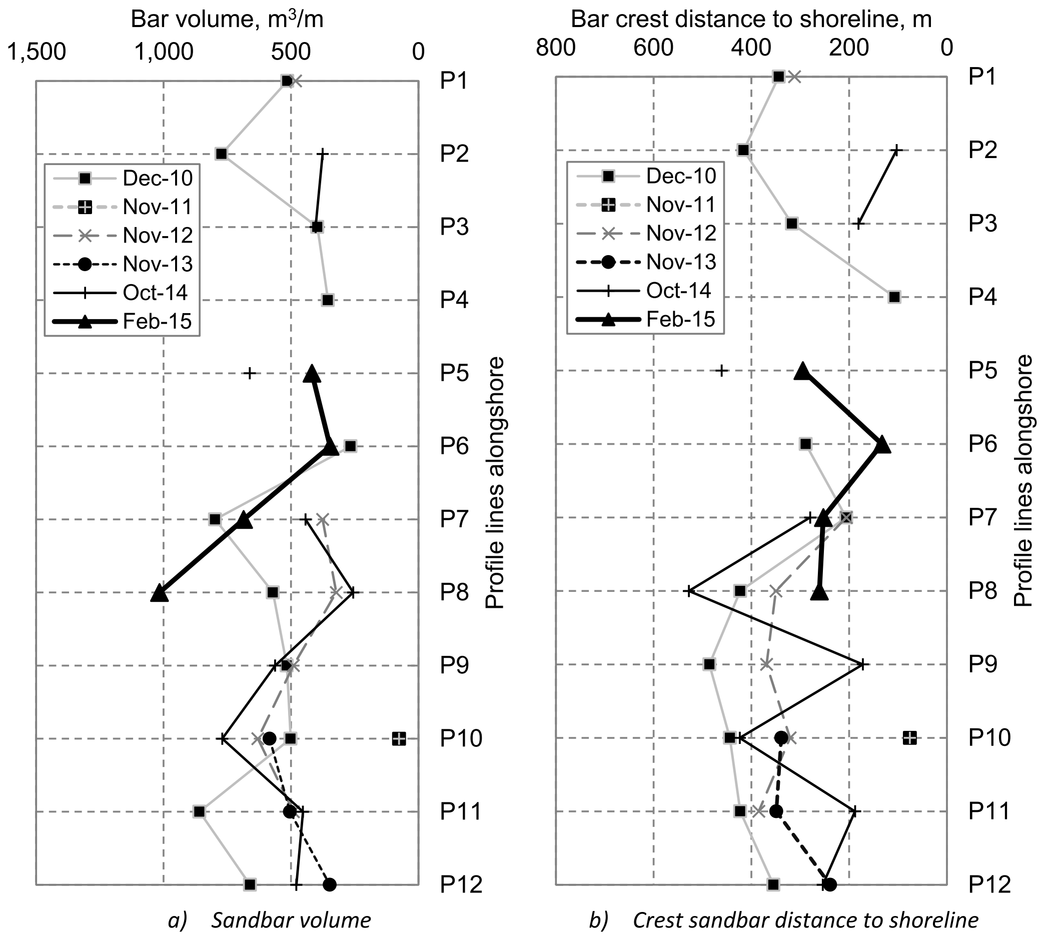


Fig. 10. Sandbar characteristics (volume and position), along profiles P1 to P12.

variations in profile morphology, also consistent with the observations displayed in Fig. 10. The accreted summer profile was eroded by the first storms (note that Nov-10 was a very energetic month, see Fig. 4), forming an offshore sandbar which lead to a positive sediment budget of around 0.45 Mm^3 in CA2A. Two years after the fill no sandbar was detected (Nov-11). However, cross-shore measurements for P6 and P7 (intercepting DA2) indicated a general profile bed elevation above −6 m (CD) elevation contour relative to Oct-09, which is in agreement with the sand accumulation manifested in Nov-11. Three years later more than 0.80 Mm^3 of sediments were eroded from CA2B (Fig. 14b), but approximately 17% (0.14 Mm^3) of the lost sediment in CA2B was stored below the level −9.5 m (CD). The intercepting profiles (P6 and P7) also exhibit a negative sediment balance between Oct-09 and Oct-12. The negative sediment balance calculated within CA2B between Oct-09 (summer profile) and Apr-13 (winter profile) is around 0.43 Mm^3 (Fig. 12), which corresponds to approximately half of the change in 2012.

The next fills in DA2 were carried out during May, July, October, and November of 2013, where the second one was the most significant (1 008 113 m^3). In CA2A, comparing the surveys of Jul-13 and Nov-13, accretion of sand close to 0.04 Mm^3 is observed, corresponding only to 20% of the total nourishment volume dumped in Oct/Nov-13. Extending the temporal scale, the general evolution of the fill placed in Jul-13 can be analyzed between Jul-13 and Sep-14 (Fig. 14d). During this time, nourishment was carried out only in Oct/Nov-13 (199 297 m^3) and as expected, the dumped material was subjected to the natural adjustment under local wave conditions, which induced a total volume loss around 0.05 Mm^3 (within the CA2B). The sediment budget in CA2B is negative during this period and more than 51% of the major fill was not detected one month later (Fig. 14c). A comparison between Sep-14 and Apr-15 was more suitable for investigating the impact of the fills performed during Sep/Dec-14. The sediment budget was calculated to be −0.36 Mm^3, which means that there is no signal from the nourishment volume added. The general sediment balance between Sep-09 and Apr-15 in CA2B is approximately 0.15 Mm^3, which corresponds to 7% of the total dumped sand volume (about 2.3 Mm^3 of sand). However, these values are also affected by seasonal morphological patterns and the fact that the dumping area DA2 is located in a very dynamic area.

4.3. EOF analysis

Fig. 15 shows the main results obtained by the EOF analysis. The data variance was concentrated in eight modes (equal to the number of surveys) that drops with the increase of the number mode. However, only a limited number of modes is needed to explain most of the variation in the data. Therefore, through the first three eigenvectors 70% of the variation in the data was explained, where the first, the second, and the third EOFs (E_1, E_2, and E_3) contributed 39%, 18% and 13%, respectively, to the total variation. The first three temporal EOFs are displayed in Fig. 15a (A_1-A_3), and Fig. 15b–e shows the corresponding spatial EOF maps (E_1-E_3).

By examining the results presented in Fig. 15, it stands out that the accretion and erosional patterns described by the first three eigenvectors (see spatial EOFs in combination with the temporal EOFs) are not completely uniform alongshore, indicating different responses from one transect to another. In these cases, a fully straight-forward physical interpretation of the modes is difficult to establish. For instance, by

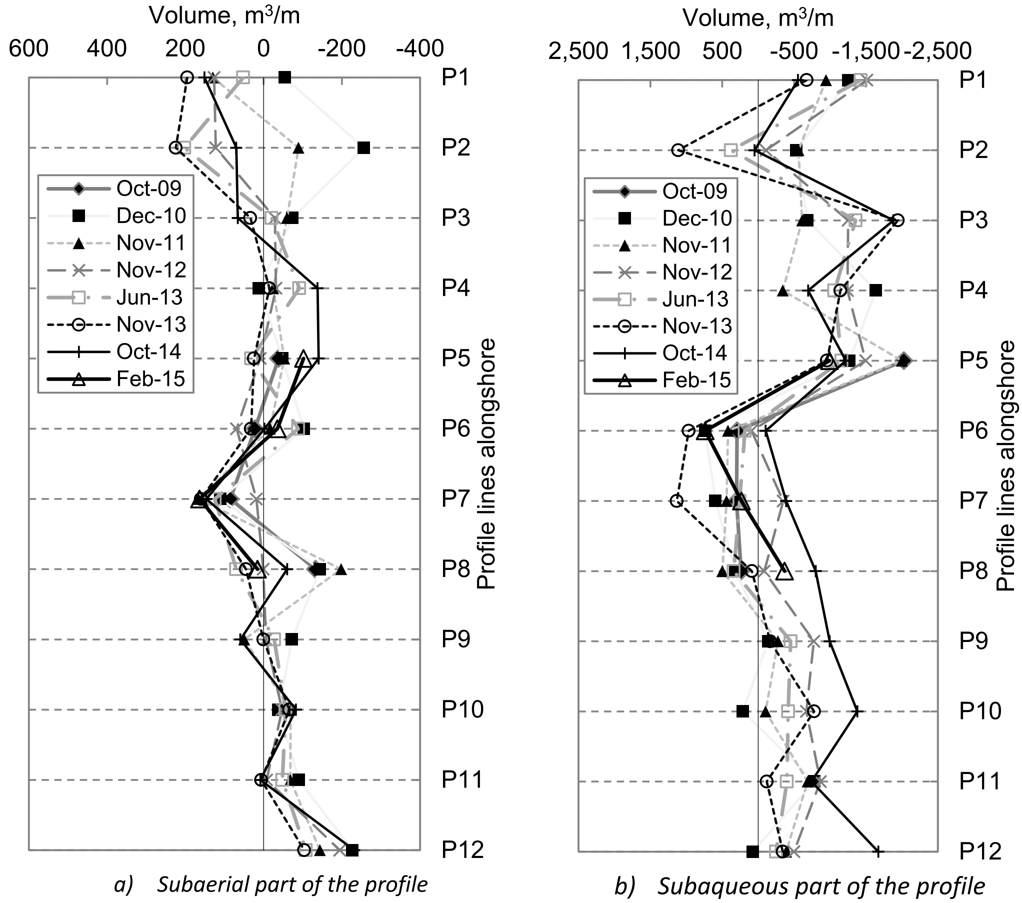


Fig. 11. Cumulative volumetric changes. Volumes relative to Sep-09 for profiles P1 to P12.

focusing on the behaviors of P7 and P8, the first spatial EOF (E_1) would be interpreted as the exchange of material between the berm and the bar region, which is in accordance with the seasonality manifested by A_1 (Fig. 15a). A positive value of A_1 would reflect the sediment movement from the onshore to the offshore, where the largest accretion of material (see E_1) typically occurs in about −7 m (CD), with residual changes seaward of this depth. A negative value of A_1 would imply the opposite development: transport from the offshore to the onshore (note that the minimum value is attained in Jun-13 when the beach profile is affected by the summer season). However, the spatial patterns of erosion and accretion highlight a sandy bar appearing during Sep-14 in profile P5, which six months later (in Feb-15) still can be observed. As discussed before, this sandbar is probably a result of onshore sediment transport, promoting nearshore sand accretion. As can be seen from Fig. 15, locations of accretion and erosion areas for specific profiles in E_1 are highly variable alongshore, P5 and P6 being clear examples of that.

Although the first three modes have explained more than 70% of the variability, the spatial variance found between profiles, which can be mainly attributed to the low spatial and temporal resolution of the

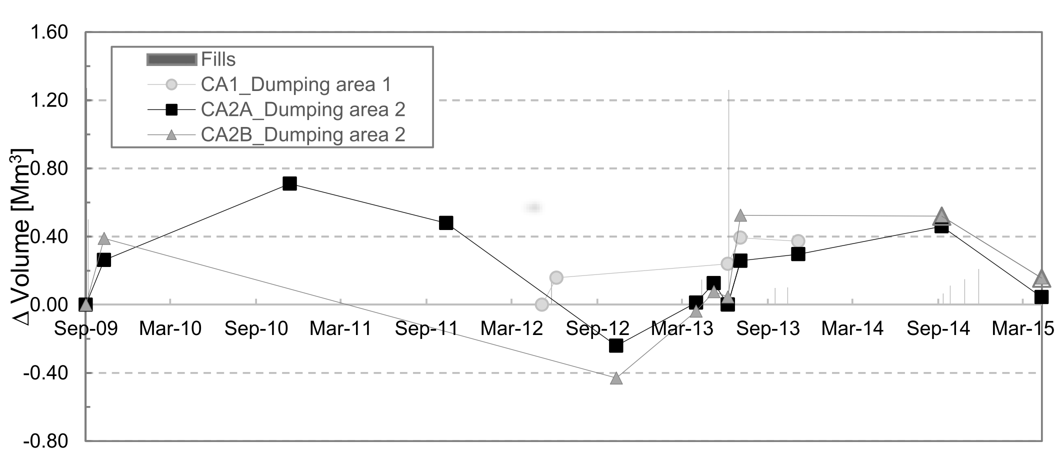
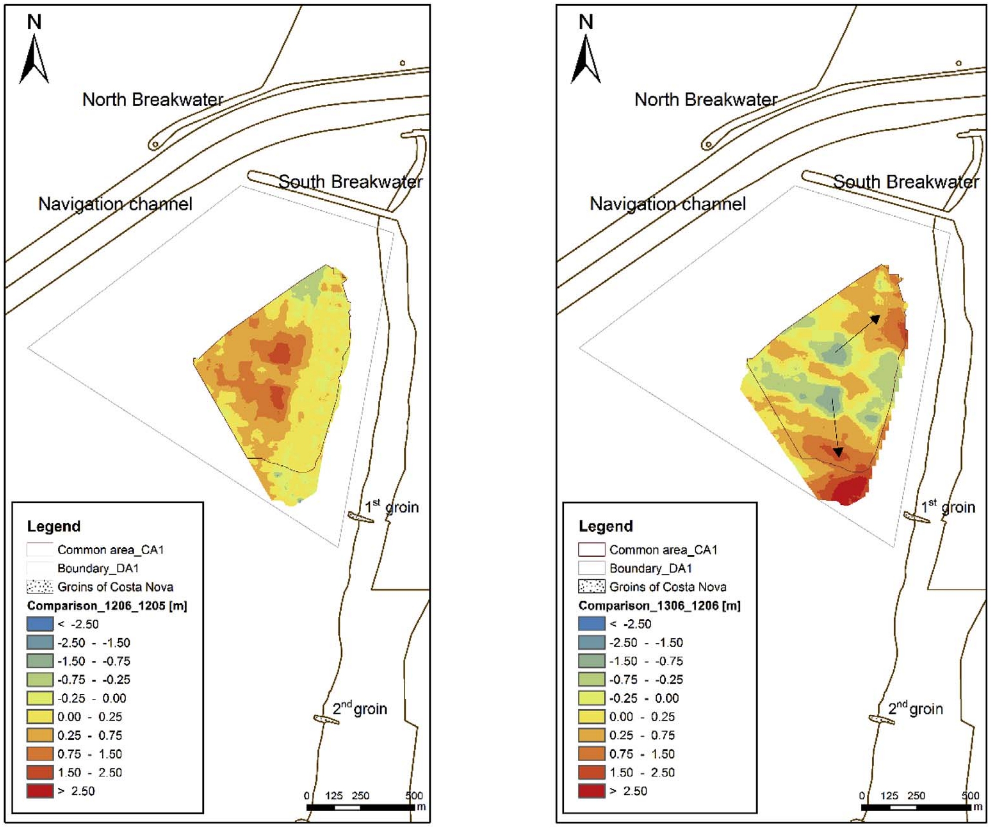


Fig. 12. Sediment balance for the dumping areas between Sep-09 and Apr-15. The bars correspond to the artificial nourishments and the symbols (triangles, circles and quadrates) to the survey events. a) May-12 and Jun-12 (1 month).



a) May-12 and Jun-12 (1 month)

Area=0.48 km^2; ΔVolume=0.16Mm^3
Nourishment volume= 169 218 m^3

b) Jun-12 and Jun-2013 (one year)

Area=0.52 km^2; ΔVolume= 0.16Mm^3
Nourishment volume= 79 061 m^3

Fig. 13. Bathymetric evolution at DA1 (bed elevation change between surveys).

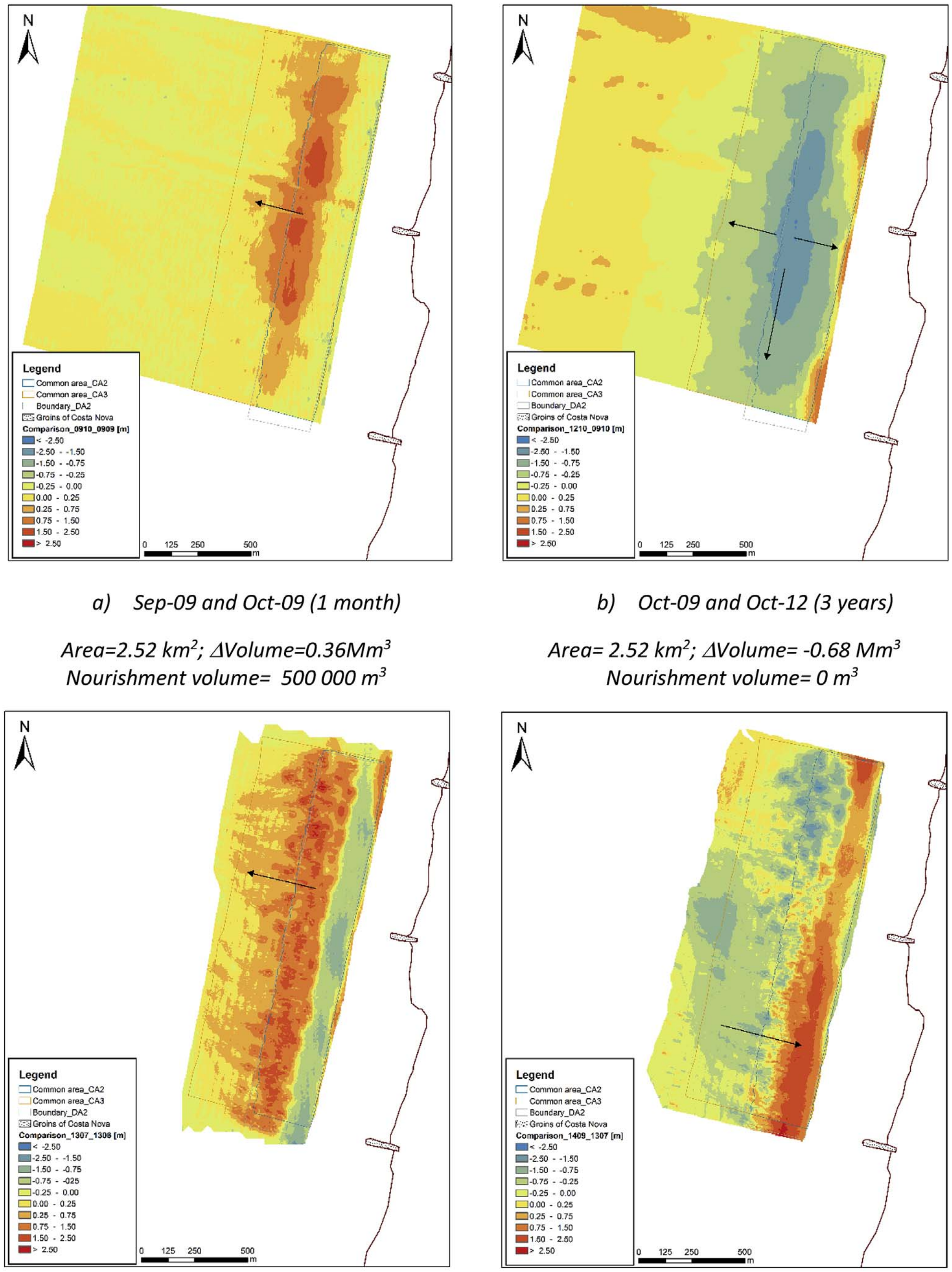
cross-shore surveys covering the DA2, prevented the initial process of fill adjustment and storm-induced changes from being observed in the data set. Considering the orthogonality hypothesis between modes, if no physical interpretation could be given to the first mode, which in principal should be alongshore coherent, the subsequent modes (2nd and 3rd) are inevitably affected.

5. Discussion

Cross-shore profile data analysis revealed that seasonal cross-shore exchange of sediment volume can exceed the total nourishment volumes; thus, the artificial bar was not visually detected (as an identifiable feature) in the cross-shore survey immediately after the first winter, indicating that the fill material has suffered a significant cross-shore distribution. In general, the field measurements collected during more than 5 years of monitoring demonstrated large cross-shore beach variability induced by strong seasonal cycles, large short-term changes of the fill material in the dumping areas, and a generalized erosion trend primarily determined by local wave conditions and a negative longshore sediment transport balance.

As opposed to the northern profiles, intercepting Barra beach, the similarity between temporal cross-shore changes for the most southern profiles (Costa Nova and Vagueira beach, P7-P12) indicate rather uniform behavior and coherence in terms of cross-shore material exchange. The shadow effect of the Aveiro Harbor breakwaters, acting as protective barrier, is a reason for the different behaviors, interfering with the natural response of the profiles located just south of the breakwaters (P3-P6). In addition, between Jun/July-13, under the same wave conditions, at Costa Nova beach (Fig. 14c) the fill material seemed to suffer a more rapid distribution, dominated by offshore directed currents than at Barra, which during certain periods showed a non-uniform sand distribution, induced by diffraction currents generated by the northern breakwater. As the surveyed dumping regions were relatively limited, significant amounts of sediments were transported across their boundaries in both the longshore and cross-shore directions. Sand volumes arising from the Barra nourishments may have been driven by longshore transport towards the southern beaches (Costa Nova). However, the influence of the cross-shore material exchange seems to be greater than that from longshore transport gradients in controlling the sediment budgets in the dumping areas. This was also concluded by Park et al. (2009) when examining the evolution of the nourished beaches in northeastern South Carolina. Although the cross-shore transport gradients and exchange of material may be larger in absolute terms than the material moved due to longshore transport gradients, the former transport often implies no net change within the profile, whereas the latter cause losses or gains of material resulting in erosion or accretion, respectively. Thus, in the long-term, the longshore transport often determines the ultimate fate of the fill.

Over the 5 years of surveying (2009–2014), an average beach profile volume change of 706 m^3/m were eroded from S. Jacinto-Vagueira coastal stretch, while approximately 2.8 Mm^3 of sand was dredged and dumped on fifteen occasions. The magnitude of the errors arising from the cross-shore surveys, mainly in the intertidal zone, is poorly known since limited measurements were available. Also, it should be stressed that the findings of this paper have to be considered with care, as the uncertainties related to the accuracy of the elevation measurements can reach 10 cm, which may imply an error in the calculations of sediment budgets ranging from ± 43 000 to ± 105 000 m^3, depending on the CA



a) Sep-09 and Oct-09 (1 month)

Area=2.52 km^2; ΔVolume=0.36Mm^3
Nourishment volume= 500 000 m^3

b) Oct-09 and Oct-12 (3 years)

Area= 2.52 km^2; ΔVolume= -0.68 Mm^3
Nourishment volume= 0 m^3

c) Jun-13 and Jul-13 (1 month)

Area=1.30 km^2; ΔVolume=0.50Mm^3
Nourishment volume= 1 008 113 m^3

d) Jul-13 and Sep-14 (14 months)

Area=1.40 km^2; ΔVolume= -0.06 Mm^3
Nourishment volume= 199 297 m^3

Fig. 14. Bathymetric evolution at DA2 (bed elevation change between surveys). Arrows represent cross-shore material exchange and longshore sediment transport predominant direction.

considered (0.43 km^2 for CA1 and 1.05 km^2 for CA2B). Regarding the profile volume changes, the influence of the decimeter accuracy (surveying error) for the subaerial portion is estimated in 20 m^3/m, representing 10% of the subaerial changes (ranging between ± 200 m^3/m), whereas for the subaqueous portion is around 245 m^3/m (16% of the maximum observed volumes variations). Although terrestrial techniques (RTK GPS) are typically between 1 and 3 cm accurate vertically, in the present study the surveying accuracy was considered larger, on the order of magnitude of airborne surveying methods (such as photogrammetry and Lidar) and video camera systems, which are mainly used when larger areas need to be covered (Blossier et al., 2017).

Areas around the profiles intercepting DA2 showed a final positive sediment balance (according to the last survey conducted in Feb-15) as well as the neighboring area around P2 (in Sep-14). This positive effect for P2 occurred simultaneously with the extension works of the Aveiro harbor breakwater (completed in 2013), whereas the accretion verified for P5-P7 is directly associated with the fills. Between Nov-13 and Sep-14, significant erosion along the entire monitored coastal stretch was observed. During the severe winter of 2013/14, with major storms hitting the study site, the average cross-shore eroded volume for the 12 lines increased from 19 m^3/m (survey just before) to 706 m^3/m (first survey after).

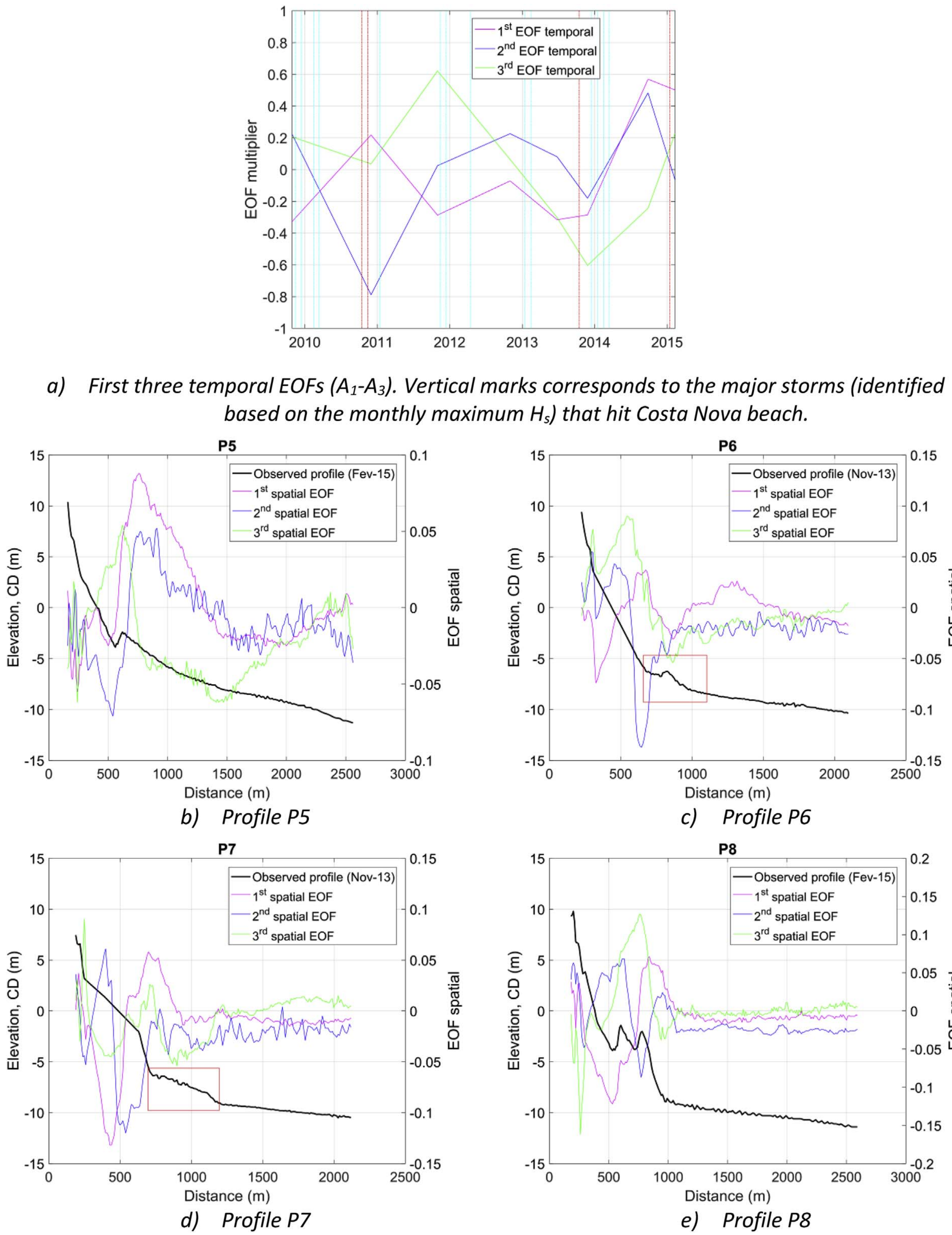


Fig. 15. First three spatial EOFs for each profile around DA2 (data from Oct-09 to Feb-15). Red squares point out the cross-shore location of the fills. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Despite the significant nourishment volumes (in total more than 2 Mm^3 of dumped sand during 2013–2014), after the first winter (bringing the first storms combined with high water levels), the nourishments could not be detected in either the cross-shore sand volumes or at the dumping locations. Because the material was dumped as nearshore deposits in the subaqueous portion of the profile, where the sediment dynamic is much stronger (Karunarathna et al., 2012), substantial offshore losses occurred, such as the one verified during Jun/Jul-13 at DA2 (approximately 50% of the fill material), even though the sand nourishments were mostly carried out in the summer.

A clear evidence of the dune system reinforcement was observed *in situ* through a significant elevation increase of the dune crest between

Sep-14 and Feb-15 for P7, P8 and P9. It is possible that the sand nourishments, carried out on the subaerial beach during the summer of 2014, may have contributed to this reinforcement. Fills performed on the subaerial beach in late summer, when the berm width reaches its maximum may stay in subaerial beach profile longer, as suggested by Yates et al. (2009), when studying fill behavior at a southern California beach. However, the results of different nourishments schemes and timing of placement on sandy beaches with strong cross-shore fluxes, arising from intense seasonal cycles, are still poorly understood (Yates et al., 2009; Jacobsen and Fredsoe, 2014; Marinho et al., 2017).

Although EOF analysis is regarded in many cases as a powerful tool for analyzing complex spatial and temporal morphological beach changes (Larson et al., 1999), here, the limited temporal and spatial coverage of the profile dataset have prevented the detection of spatial patterns in a short and long-term basis, leading to a set of physical meaningfulness modes.

Extended spatio/temporal analysis of monitoring data was performed, but several uncertainties remained, pointing out the importance of adjustments at different levels the monitoring programs to the intended analysis. However, several typified behaviours could be identified. The main limitation to the analysis performed was the lack of a more systematic and comprehensive monitoring campaigns undertaken *in situ*, preventing the tracking of the nourished sand and consequently a better assessment of the cross-shore processes responsible for the sand distribution in the cross- and longshore direction. Given the uncertainties associated to the measuring accuracy, this was also considered a limitation.

6. Conclusions

In this paper, GIS techniques and EOF analysis were employed as the main tools to investigate a monitoring data set of the morphodynamic evolution of Barra-Vagueira coastal stretch in connection with several beach fills. Beach topo-hydrography surveys at 12 profile lines, distributed evenly along the study site, as well as detailed bathymetric data collected in the dumping areas before and after nourishment operations, were available.

Profile observations collected over more than 5 years of monitoring demonstrated a larger influence on the beach evolution from the seasonal cycle of cross-shore material exchange than from the nourished sand (representing 13% of total profile data variability); after the first winter the fill material could not be detected. The storm surges, that commonly hit the study site, make it liable to large topo-hydrographic changes with immediate impacts on the cross-shore sediment transport and marked effects on the sediment budgets. The most critical period, revealing a widespread erosion, was recorded during the energetic winter of 2013/2014, which has contributed to an average cross-shore eroded volume from $19\,m^3/m$ to $706\,m^3/m$ for the entire study area. This behavior was also recognized when evaluating the short- and medium-term responses of the fills in dumping areas, revealing a pattern of offshore directed losses. This implies that the cross-shore material exchange, also identified during periods of low-energy waves, is an important controlling factor for the sediment budget in this coastal system.

Furthermore, profile evolution indicators and bathymetric data analysis lead to the conclusion that the nourishments carried out at the study site had a positive influence on the beach evolution, showing a larger efficiency for the most nourished area (DA2). Despite their small-scale effects, correlated analyses showed that southern neighboring areas may be benefiting from fill material, confirming the feeding behavior of the nourishments (as evidenced from profile P5 and DA1 evolution).

Although it was possible to associate some changes in the beach morphology to the hydrodynamic forcing events, fill placements, and some sediment transport mechanisms, the limited set of conclusions drawn in this paper highlights that the monitoring strategy established in DIA falls short, compromising the follow-up studies and an accurate judgment of the project performance. For revealing patterns in data sets on beach morphology that are spatially and temporally sparse, the application of EOF analysis proved to be a weak tool, highlighting the importance of better quality data to achieve adequate evaluations. How the nourishments have been responding on short-term basis, but especially in a long-term perspective or how the disposal activities of the dredged material have been contributed to alleviate or minimize the erosion trend southward of the Aveiro Harbor, still remains unanswered, raising the question about the suitable approach for surveying. A lesson to be learned from this case study, which can be also valid for meso-tidal beach environments, is that a more systematic monitoring plan and comprehensive data collection should be established. Equally important is that highly accurate electronic surveying instruments, in order to collect high-density data accurately and efficiently within a selected time, should be used for supporting future beach management processes. Regular surveys throughout the year, including prior to dredging and periodically thereafter, will help capturing important cross-shore changes (such as the initial adjustments of the fill) and establishing a solid baseline for investigating fill responses, regarding time evolution and performance with a high level of confidence. Contingency plans for collecting surveys immediately after storms should also be included, so that post-storm conditions of the project and storm-induced beach changes may be documented.

Extending the monitoring of the dumping areas not only in the cross-shore direction (landward/seaward) but also alongshore is encouraged for a better assessment of the beach fill functionality. A higher spatial resolution of the surveying will also help to obtain detailed insights into the governing processes and the forcing conditions that determine the fill evolution, offering means of attempting to maximize the potential of nearshore accretion and providing a basis for developing guidance for engineers and planners regarding the best practices for fill placement. Future monitoring would benefit from site inspections concurrently with the profile surveying, describing any relevant information that could characterize the subaerial beach state (*e.g.*, evidence of movement of the fill material, dune foot position, unusual erosion or accretion, presence of dune or berm recovery signs, vegetation level, effects of storms such as scarping or overwash) as a way to support the campaigns *in situ*. In conclusion, this paper stresses the importance of a systematic data analysis being developed as part of the monitoring activities, providing tools for identifying problems as well as the development or re-adaptation of solutions.

Acknowledgements

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Appendix A. EOF Analysis

EOF analysis, also termed principle component analysis (PCA), is a data reduction technique applied to describe the variation of a data set by a small number of independent functions extracted from the data itself (Preisendorfer, 1988; Jackson, 1991). These functions correspond to a statistically optimal description of the data with respect to how the variance is concentrated in modes, where the variance explained decreases with the mode number. Each of these modes of variability comprises a spatial and a temporal component, where the first (lowest) mode explains the greatest percentage of the data variation. In this way, only a limited number of modes are needed to explain most of the variance in the data set. Although the

EOF is strictly a data analysis tool with no inherent physical background, physical interpretations are possible in many cases, relating the results of the EOF analysis to morphological features and related physical mechanisms (Larson et al., 1999; Lemke et al., 2014).

A data matrix D containing, for example, bottom topographies sampled in space (columns) at specific times (rows), may be represented using matrices involving the spatial EOFs (E, *i.e.*, principal components), the eigenvalues L, and the temporal EOFs (A, *i.e.*, principal component scores):

$$D = ELA^T \tag{1}$$

The column vectors in E and A are orthonormal and correspond to the eigenmodes, and the variance associated with respective mode is given by the eigenvalue in L. The EOFs are usually obtained by solving an eigenvalue problem involving the covariance or correlation matrix based on D, but in some applications the sum-of-square matrix is used instead. In the former approach the arithmetical mean is removed which is the most common method in applications to morphologic data, because the mean tends to dominate the signal (Larson et al., 1999).

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PAPER IV

Marinho, B., Coelho, C., Larson, M., Hanson, H. **(2017);** *Cross-shore modelling of nearshore bars at a decadal scale.* Marine Geology, Elsevier (under review).

CROSS-SHORE MODELLING OF NEARSHORE BARS AT A DECADAL SCALE

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Abstract: This paper presents a numerical model of subaqueous cross-shore profile behavior, including longshore bar evolution, the response of feeder mounds, and the coupling between the subaerial and subaqueous profile evolution. The present model development builds on the semi-empirical model proposed by Larson *et al.* (2013), designed to simulate the evolution of longshore bars exposed to incident waves, as well as the exchange of material between the bar and the berm region. Here, efforts are made to expand the theory for the evolution of a single-bar to a two-bar system, where the volumes of the individual bars and their responses are modeled. The modelling is carried out for an inner and an outer bar, where the outer bar is of primary interest with the purpose of predicting the behavior of placed dredged material. The wave-driven cross-shore transport rate is based on the evolution equation for the bar system response to the hydrodynamic forcing by reference to its equilibrium condition, where the change in the bar volume is based on a set of wave criteria describing the onset of a new breaking zone when the outer bar forms. Empirical formulas are employed for the bar equilibrium volume and for coefficients determining the bar response rate. The model is first calibrated and validated against data from Duck, North Carolina, USA, where two bars typically appear. Field data derived from nearshore sand placement projects (Silver Strand State Park, California, and Cocoa Beach, Florida, USA), involving the construction of artificial longshore bars, are also employed to test the model in complex situations with diverse wave climates and typical beach profile shapes. The study presented in this paper shows that the equilibrium-based model is skilled at predicting the time-varying volume of the outer bar (ε=0.39; NMSE=0.24), suggesting that this morphological feature is strongly influenced by offshore wave forcing in a predictable, equilibrium-forced manner. Model skill was lower (ε=0.51; NMSE=0.29) when predicting the inner bar evolution at Duck, remaining questions about the predictability and the equilibrium-driven cross-shore behavior of

more transient features. Model prediction of the evolution of feeder mounds (artificial bars) proved to be also successful through description of hypothetical bars characterized by zero equilibrium bar volume, leading to a good agreement with the field observations. Overall, the potential for using rather simple models to quantitatively reproduce the main trends of cross-shore volume changes in bars in a time perspective from years to decades has been demonstrated.

Keywords: subaqueous response, longshore bars, sediment transport, artificial nearshore placement, multi-bar system, shoreline evolution.

1. INTRODUCTION

Many wave dominated sandy coastal systems across the world are characterized by the presence of one or more subtidal longshore bars (Larson and Kraus, 1992; Ruessink and Kroon, 1994; Różyński and Lin, 2015; Ruggiero *et al.*, 2016; Bouvier *et al.*, 2017; Walstra and Ruessink, 2017; Aleman *et al.*, 2017; Stwart *et al.*, 2017). For such systems, models are required for simulating the bar-berm material exchange to reproduce: 1) the seasonal behavior of the beach profile; 2) the effects of the sediment release during storms from the dune and the beach to the subaqueous portion of the profile; and 3) the recovery process of the berm during periods of low-energy, when bars tend to lose volume and migrate onshore (eventually welding to the shore).

In support of coastal engineering and management activities, during the last few decades, a strong demand for sophisticated, robust, and reliable models for simulating coastal evolution over decades to centuries has emerged. The earliest type of long-term coastal evolution models focused on predicting the shoreline evolution in response to the potential sediment transport gradient generated by incident wave energy, following the one-line theory. According to this theory, firstly introduced by Pelnard-Considère (1956) and numerically implemented by numerous authors since then, beach profile moves parallel to itself, maintaining an equilibrium configuration. Thus, one-contour line can be used to describe changes in the beach shape and volume during accretionary and erosional events. Some examples of such models are GENESIS (Hanson, 1988), Unibest CL+ by Deltares, LITPACK (LITLINE) by DHI and LTC (Coelho, 2005). Although, these models can be used at large temporal (annual-decadal) and spatial scales (kilometers), one of their weaknesses has been the simplified representation of the cross-shore (CS) material exchange, where usually CS processes are incorporated through sink or source terms with representative values in time and space.

Profile evolution models, on the other hand, are commonly used to simulate the beach change on a short-term basis (hours to days), for investigating the impact of individual storms in the beach-dune system evolution, as well as the response of beach fills under storm conditions, *e.g.*, SBEACH (Larson and Kraus, 1989), LITPACK (LITPROF) by DHI, XBEACH (Roelvink *et al.*, 2009), but also on a short- to medium-term (month to year) like Unibest TC, by Deltares. Nearshore morphology models simulating storm-induced changes have been widely applied for the last decade and demonstrated an acceptable level of accuracy as a result of well-defined cross-shore sediment transport equations, established numerical solutions, and high-quality field and laboratory data (Smith *et al.*, 2017).

According to Larson *et al.* (2016), to improve the predictive capabilities of coastal evolution models, physics-based formulations need to be employed for calculating CS exchange, although schematizations of the governing processes are required to reduce the computational effort. A proper balance between physical descriptions from theoretical considerations and empirical information based on data and observations is the key for simulations addressing large areas and long time periods that will yield useful simulations results. Larson *et al.* (2013) developed a semi-empirical model to simulate the long-term response of longshore bars to incident wave conditions, as well as the material exchange between the berm and bar region. In this model, the variation in the bar volume is taken to be proportional to the deviation from its equilibrium condition and coupled to the berm response (*i.e.*, bar growth implies a decrease in the berm volume and vice-versa). Subsequently, Larson *et al.* (2016) combined this model with modules to calculate dune erosion, overwash, and wind-blown sand (forming a unique-coupled system), in order to simulate the evolution of a schematized profile at a decadal scale. As a first attempt towards modelling regional cross-shore evolution, this model, known as the CS-model, was developed to fill the gap between a sediment budget approach and a detailed profile evolution model. This model has been successfully validated by Palalane *et al.* (2016) for several field sites around the world (Portugal, Mozambique, and Sweden). The dynamics of selected CS processes was modeled based on physically based expressions, whereas the longshore transport is included in a simplified way through a continuous sink or source applied to the shoreline position.

The objective of the present study is to enhance and validate a numerical approach developed in an equilibrium fashion to predict the subaqueous cross-shore beach profile response for applications in coastal evolution models, describing processes at the decadal scale. Following the modelling approach proposed by Larson *et al.* (2013), efforts are made to expand the theory of the evolution of one single bar to a multi-bar system, where the volume of the individual bars and their response are described, but without regard to the details of the profile/bar shape or how the material may be deposited in or removed from the surf zone. The actual sediment transport paths resulting in the bar evolution are complex and contributions from both shoreward and seaward sides are expected. As a first step, a two-bar model is developed and validated with field data from Duck, North Carolina, where two bars (inner and outer) frequently form. To the author's knowledge, this is the first attempt to model the exchange of material of a multi-bar system. The prediction of the outer bar response is seen of particular interest in this study, because it is located in water depths where, for instance, typically available equipment can access for nearshore placement of dredged material, providing a method for estimating the response of offshore mounds (artificial bars). Also, it is understood that when disturbing the natural conditions (as the example of the offshore mounds), it may be possible to observe strong signs/responses in the beach morphology, offering a mean to investigate the bar behavior in a more fundamental way, as marked perturbations to the system have occurred.

In recognition of the potential attributes of placing material nearshore for serving as a reservoir of sand in promoting beach growth and the dissipation of wave energy, several reports about nearshore disposals have been published, for example, Andrassy (1991), Bodge (1994), Larson *et al.*, (1999), Barnard *et al.* (2006), Larson and Hanson (2015), Smith *et al.* (2017), and Marinho *et al.* (2017a; 2018b). Although material placed in the nearshore becomes a part of the littoral system, benefits to the beach are still difficult to quantify. The present model was also employed to numerically solve hypothetical bar equations representing offshore mounds as they migrate towards the shore and become a part of the beach face. The model was applied to simulate nearshore sand placements as hypothetical natural bars for cases from Silver Strand, CA, and Cocoa Beach, FL, where in the latter case natural subtidal bars were not found.

This paper is structured as follows. First, a brief review about the semi-empirical model proposed by Larson *et al.* (2013) is given, as this form the basis for the theoretical developments of the two-bar model, which is described thereafter (section 2). Selected cases studies are addressed in section 3 through model application and a discussion of the numerical results. Final conclusions are drawn in section 4.

2. MODEL DESCRIPTION

2.1. Theory for one bar and evolution equation

The subaqueous model developed to simulate bar-berm material exchange is briefly reviewed in this section, since a comprehensive description about the theoretical development is given in Larson *et al.* (2013, 2016) and Marinho *et al.* (2017b).

Briefly, as waves break near the shore, energy is dissipated producing a turbulent fluid environment where sediment is entrained and maintained in suspension. Depending on the vertical profile of both the cross-shore fluid velocity field and the sediment concentration, the sediment will experience net onshore or offshore movement, resulting in a berm or bar profile. Sediment transported in the offshore direction will drop out of the water column to be deposited where the turbulence begins to decrease, somewhat seaward of the plunge point, where breaking waves undergo maximum energy dissipation (Miller, 1976; Skjelbreia, 1987). In the field, a berm is formed as sediments are transported onshore and drop out on the foreshore, for which the force of gravity and properties of the uprush bore determine the berm height (Sunamura, 1975). In this study, the type of bars that are empirically investigated are those formed by wave breaking on beaches exposed to moderate or high wave energy conditions with a moderate tidal variation. Waves approaching shore on a sloping beach increase in height due to shoaling until depth-limited breaking occurs. The condition for incipient breaking is a function of the local beach slope (accounted in a direct way by means of the equilibrium beach profile) and the wave steepness.

According to Splinter *et al.* (2018) the outer bar and the shoreline positions move in opposite directions to changes in the annual offshore wave forcing. Thus, the proposed model assumes that the exchange of material between the bar and the berm takes place under sediment volume conservation, which means that no material is lost offshore. Material needed to supply the bar is mainly taken from the region of the inner surf zone, resulting in erosion of the subaerial beach. This process keeps taking place until a stable beach profile is achieved which dissipates wave energy without significant changes in shape. To reproduce this mechanism the volume eroded from the berm is stored in one offshore bar (or, its representative morphological volume) that will reach a certain equilibrium volume (V_{BE}), if the wave conditions are steady and the sediment grain size does not vary (Larson *et al.*, 2013). However, the beach state subjected to steady wave conditions is only an idealized situation since the natural wave regime is never steady for extended periods of time. Instead, cross-shore profiles are in constant change, *i.e.*, in dynamic equilibrium, with different time scales of morphological responses. So, in the model if the bar volume (V_B) at any given time is smaller than V_{BE}, then the bar volume will grow, whereas the opposite ($V_{BE} < V_B$) implies a decay in the bar volume. Consequently, growth in bar volume causes the corresponding decrease in berm volume (or shoreline retreat), and decay in bar volume causes an increase in berm volume (or shoreline advance). Figure 1 illustrates the cross-shore exchange of material between the subaqueous (bar) and subaerial (berm) portion of the profile.

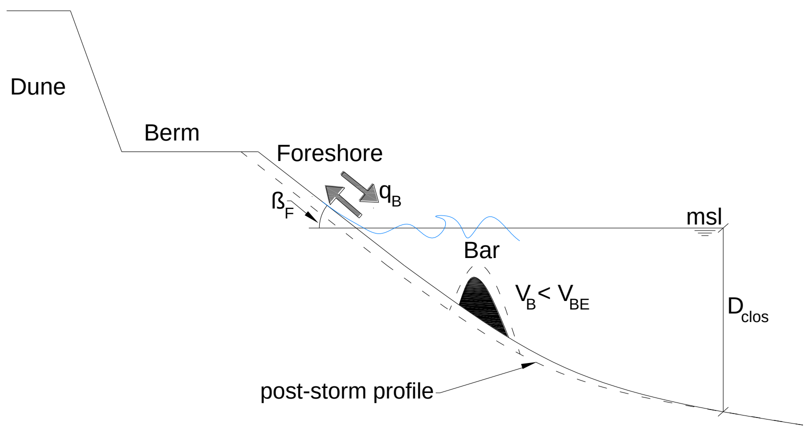


Figure 1. One-bar theory. The variables q_B, β_F, and D_{clos} denote the subaqueous transport rate between the bar and berm, foreshore slope, and depth-of-closure, respectively.

The change in bar volume is taken to be proportional to the deviation from its equilibrium value,

$$\frac{dV_B}{dt}=\lambda(V_{BE}-V_B) \tag{1}$$

in which λ is a coefficient quantifying the rate at which equilibrium is approached. This coefficient depends on the sediment grain size (or fall speed, w), wave height (H_0), wave period (T), and the λ_0 and m coefficients, which should be calibrated against data, according to:

$$\lambda=\lambda_0\left(\frac{H_0}{wT}\right)^m \tag{2}$$

A representative beach slope is implicitly contained in the fall speed (or grain size) because the equilibrium beach profile depends on this quantity (Dean, 1987).

Observations of bar response to storms (*cf.*, Larson *et al.*, 2016) indicate that bars would exhibit a relatively larger growth in the field during energetic wave conditions, whereas the recovery process would be slower (during periods of calmer waves). An additional factor is used to adjust the coefficient λ_0 ($\lambda_0^{on}= C_c^{on}\lambda_0$; $\lambda_0^{off}= C_c^{off}\lambda_0$) when onshore or offshore sediment transport occurs ($V_{BE}<V_B$ and $V_{BE}>V_B$, respectively) as a way to better reproduce the observed bar behavior in the field, defined by a relatively slower response during onshore sediment-transport driving mechanisms (Larson *et al.*, 2016). Larson *et al.* (2016) suggested suitable values for m (=-0.5) and for λ_0 ($0.15h^{-1}$ and $0.002h^{-1}$, when applying Eq. 2 to laboratory and field data, respectively). Qualitatively, a larger value of λ produces a rapid response toward equilibrium. This parameter was also found by Davidson *et al.* (2013) and Splinter *et al.* (2018) to be a key parameter when quantifying the degree of disequilibrium term to express the time-varying position of the shoreline and sandbars.

In order to apply Eq. 1, the equilibrium bar volume (V_{BE}) also needs to be determined. According to Larson and Kraus (1989), it is desirable to use non-dimensional quantities to obtain general and physically-based relationships relating morphologic features to wave and sand parameters. Based on large wave tank (LWT) experiments under near-prototype wave and beach conditions (for monochromatic waves), Larson and Kraus (1989) developed an empirically based expression for V_{BE}, where the normalized equilibrium bar volume was shown to depend on the dimensionless fall speed ($\Omega=H_0/ w/T$) and the deep-water wave steepness (H_0/L_0),

$$\frac{V_{BE}}{L_0^2}=C_B\left(\frac{H_0}{wT}\right)^{4/3}\frac{H_0}{L_0} \tag{3}$$

in which L_0 is the deep-water wavelength and C_B is a dimensionless coefficient. According to Eq. 3, a larger wave height implies a larger bar volume and a greater fall speed (or larger grain size) implies a smaller bar volume (Larson and Kraus, 1989). For more information about the correlation and regression analysis detailing the degree of dependencies between variables consult Larson and Kraus (1989). Larson *et al.* (2016) obtained different values on C_B when applying Eq. (1) for predicting bar volume evolution during laboratory experiments and field observations (0.028 and 0.08, respectively).

Considering realistic wave input, Eq.1 has to be solved numerically. For each time step Δt, the wave and sediment properties will be constant (V_{BE} and λ are constant values), and so, the following analytical solution is employed,

$$V_B(t)=V_{BE}+(V_{B0}-V_{BE})e^{-\lambda t} \quad (4)$$

where V_{B0} is the bar volume at t=0. The bar volume changes equation (Eq.1) is applied during the growth and decay process of the bar, so, if $V_{BE}>V_{B0}$ the bar will grow (with sediment from the berm) and if $V_{BE}<V_{B0}$ the bar volume will decay (transferring sediment to the berm). Thus, the change in bar volume (ΔV_B) during Δt is given by,

$$\Delta V_{B,i}=\left(V_{BE,i}-V_{B,i}\right)(1-e^{-\lambda_i \Delta t}) \quad (5)$$

where subscript i denotes a certain time step. The new volume at time step i+1 is obtained from $V_{B,i+1}=V_{B,i}+\Delta V_{B,i}$. With the knowledge of the initial conditions (V_{B0}) and the input wave conditions, Eq. 5 can be used to calculate the evolution of the bar volume, both during growth and decay.

2.2. Theory for two bars

2.2.1. Two-bar evolution equation

Reports with focus on the response of multiple bar systems have been disseminated, *e.g.*, Lippmann *et al.*, 1993; Ruessink and Kroon, 1994; Grunnet and Hoekstra, 2004; Pruszak *et al.*, 2008; Kroon *et al.*, 2008; Różyński and Lin, 2015; Aleman *et al.*, 2017. At multi-sand bar sites, waves may repeatedly break and reform as they propagate towards the shore. Consequently, the behavior and alongshore variability of inner bars and the shoreline position is often influenced by wave breaking patterns on the outer bars. Several theories have been advanced to explain the formation of longshore bars. Almar *et al.* (2010), for instance, concluded that the outer bar was most influenced by the offshore waves while the inner bar dynamics were most influenced by the tide range. When the outer bar undergoes a net offshore migration and degenerates, some authors report that the shoreline and inner bar are more exposed to wave energy and vulnerable to subsequent storm erosion (Price and Ruessink, 2011; Splinter *et al.*, 2016). Ruessink and Terwindt (2000) presented a conceptual model to describe the cyclic behavior of offshore migrating bars. Following this model, a bar goes through three main stages: it is generated close to the shore (in the inner nearshore; stage 1), it migrates seaward through the surf zone (stage 2), and eventually decays at the outer margin of the nearshore (stage 3). Although important insights into the governing processes of interaction between the seabed and the wave forcing have been achieved by several authors regarding the behavior of longshore bars, the actual sediment transport mechanisms determining the bar evolution are still poorly understood by researchers to be parameterized in detail. According to Ruessink and Kroon (1994), bar parameters (such as volume, height, and mean water depth over the bar crest) can be well-linked to the bar stage. Correlations between bar and wave properties have also been discussed by Larson and Kraus (1992).

Here, bar generation by depth-limited breaking waves is considered. The semi-empirical model developed for one-bar systems have been successfully applied to several sites, also in combination with a dune erosion model (Larson *et al.*, 2013; 2016), suggesting that this equilibrium approach may be also suitable to examine equilibrium behavior of other sand-bar systems. Similar to the one-bar systems, as waves break near the shore, energy is dissipated producing a turbulent fluid environment where sediment is entrained and maintained in suspension. Depending on the vertical profile of both the cross-shore fluid velocity field and the sediment concentration, the sediment will experience net onshore or offshore movement, resulting in a berm or bar profile. Aiming to improve the one-bar model performance, a system consisting of two bars was studied, namely an inner and an outer bar. A simple wave criterion is proposed for predicting the onshore and offshore movement of the inner and outer bar with reference to their equilibrium condition.

Overall, when waves are small, only an inner bar forms. However, during high-energy wave conditions (*e.g.,* storms), large waves will break offshore and form an outer bar as well. These large waves will reform in the trough and eventually shoal and break again closer to the shore, resulting in a second but smaller inner bar in the same manner in which the most seaward main breakpoint bar was formed. Dissipation of energy decreases in the reformed waves, implying a corresponding decrease in the transport rate. The described mechanism is valid for both plunging and spilling breakers (both producing a trough in the profile shoreward of the break point), although the time scale of bar development will be longer under spilling breakers (Sunamura and Maruyama, 1987). For a multi-bar model, a method or criterion is needed to define how many bars will form for certain wave conditions and sediment characteristics. At the present model development, since the focus is on a two-bar system, a simple approach is desirable and a criteria based on the wave characteristics is employed. If the incoming wave height is greater than a certain wave height (hereafter referred as the critical wave height, H_c) then two bars will develop, otherwise, when $H_0<H_c$, the system strives towards only one bar.

The bar volume, as in the one-bar system, is taken as indicator of the transport direction, where here a growth in the outer bar volume is associated with a net seaward movement of sand and a decay in the outer bar volume is caused by onshore sediment movement (inducing degeneration of the outer bar). This assumption does not necessarily preclude the model from being able to capture inter-annual cycles and trends in sandbars, as well as shorter (storm) scale response. The inter-annual cyclic bar behavior is included *per se* since the bars in the two-bar model responds to the wave forcing at the input time scale. The build-up of the outer bar is taken as an intermittent process confined to the occurrence of high-energy periods.

It was earlier demonstrated by Larson *et al.* (2013, 2016) that the empirical equation for the equilibrium bar volume could be employed to calculate the total sediment volume stored in the inner and outer bar at Duck. Thus, this equation will be used for a multi-bar system to obtain the sum of the inner and outer bar volumes at equilibrium state. The normalized equilibrium bar volume is then given by,

$$\frac{V_{BE}^{TOT}}{L_0^2} = \frac{V_{BE}^{I}}{L_0^2} + \frac{V_{BE}^{O}}{L_0^2} \tag{6}$$

where the superscript TOT, I and O denote total, inner, and outer equilibrium bar volume, respectively. The question arises on how to partition V_{BE}^{TOT} between V_{BE}^{I} and V_{BE}^{O}. Defining the ratio $\delta = V_{BE}^{O}/V_{BE}^{I}$, then:

$$V_{BE}^{I} = \frac{1}{1+\delta} V_{BE}^{TOT} \tag{7}$$

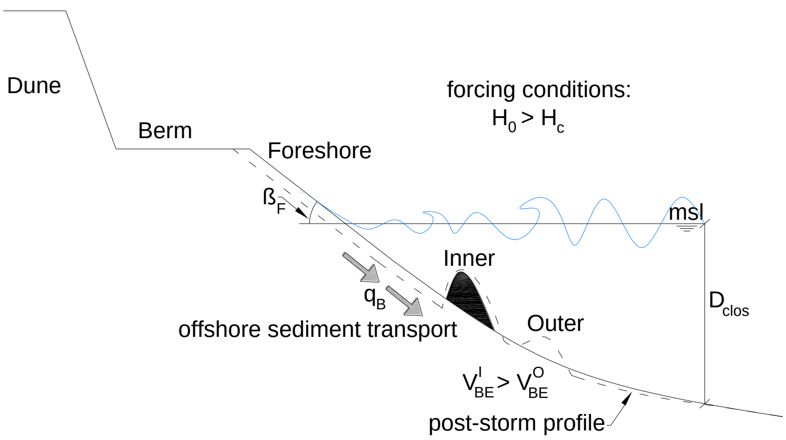
$$V_{BE}^{O} = \frac{\delta}{1+\delta} V_{BE}^{TOT} \tag{8}$$

These equations yield how much of the total bar volume belongs to the inner and outer bar, respectively. If δ can be predicted, by using Eqs. 7 and 8, V_{BE}^{I} and V_{BE}^{O} can be determined. At a first order approach, δ should depend on the relationship between H_0 and H_c; that is, a larger wave height with respect to the critical wave height (H_c) will produce a relatively larger offshore equilibrium bar volume. Based on this observation, the following empirical relationship is proposed:

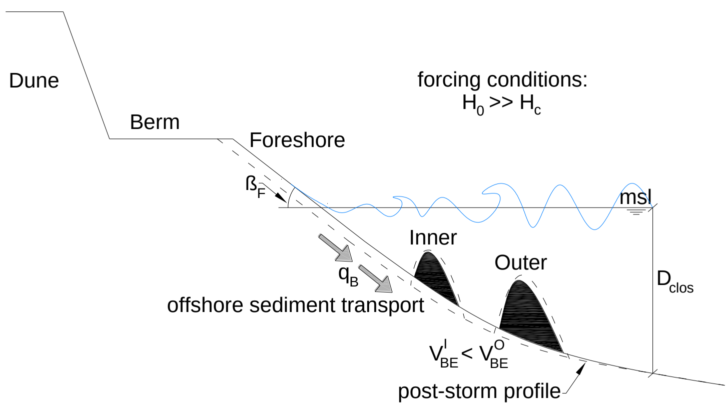
If $H_0<H_c$, then $$\delta=0 \tag{9}$$

Otherwise, for $H_0>H_c$ $$\delta=\delta_0\left(\frac{H_0}{H_c}-1\right) \tag{10}$$

where δ_0 is an empirical coefficient to be calibrated against data (=1 as a first estimate). The subaqueous processes that build the two-bar system are represented in Figure 2. If $H_0<H_c$, then the outer bar will not form or will tend to disappear ($V_{BE}^{O}=0$), whereas $H_0>>H_c$ means that the outer bar will grow relatively larger in relation to the inner bar ($V_{BE}^{O}>>V_{BE}^{I}$).



a) For 0<δ<1, the outer bar starts to form and grow.



b) For δ>1, the outer bar grows relatively larger than the inner bar.

Figure 2. Evolution model for a two-bar system.

2.2.2. Numerical solution

For each wave condition (at a specific time step), Eqs.7 and 8 together with Eqs.9 and 10 are solved numerically. The change in the inner and outer bar volume is computed in the same manner as for the one-bar system using the analytical solution described in Eq.5,

$$\Delta V^{I}_{B,i}=\left(V^{I}_{BE,i}-V^{I}_{B,i}\right)(1-e^{-\lambda^{I}_{i}\Delta t}) \tag{11}$$

$$\Delta V^{O}_{B,i}=\left(V^{O}_{BE,i}-V^{O}_{B,i}\right)(1-e^{-\lambda^{O}_{i}\Delta t}) \tag{12}$$

where subscript i denotes a certain time step. The new volume at time step i+1 is obtained from $V^{I}_{B,i+1}=V^{I}_{B,i}+\Delta V^{I}_{B,i}$ (for the inner bar) and $V^{O}_{B,i+1}=V^{O}_{B,i}+\Delta V^{O}_{B,i}$ (for the outer bar). The λ coefficient, in Eqs.11 and Eq.12, will depend on whether the inner or outer bar grows or decays. However, as the inner and outer bars are located at different water depths, different behavior should be expected. According to Larson and Kraus (1992), once the outer bar is formed, it will only be exposed to wave breaking and large sand transport during severe storms, with the transport induced by non-breaking waves producing slower changes in the bar shape. On the other hand, the inner bar experiences wave breaking during most of the year, resulting in relatively faster response compared to the outer bar ($\lambda^{O}_{0} < \lambda^{I}_{0}$). Also, when onshore sediment transport and bar volume reduction occurs, a different multiplier ($\lambda^{on}_{0}=C_c\lambda_0$) to reduce the coefficient λ_0 should be adopted for the inner and the outer bar: $C^{I}_{c} > C^{O}_{c}$ (the values of these coefficients should be determined through calibration against data).

As an exchange of material continually takes place within the surf zone, depending on changes in the nearshore wave conditions, it might be necessary to include an exchange between the inner and the outer bar volumes in the calculations.

In cases that no exchange of material is admitted between the inner and outer bar, the total bar volume going into or from the subaqueous portion of the profile is defined by:

$$q_B(t)=\Delta V^{TOT}_{B}/\,\Delta T,\ \text{where}\ \Delta V^{TOT}_{B} = \Delta V^{I}_{B} + \Delta V^{O}_{B} \tag{13}$$

The offshore or onshore sediment transport volume (from the berm to the bars or from the bars to the berm, respectively) is given by the sum of the total variation for both bars (inner and outer).

For cases where exchange of material between the bars is admitted, the outer bar volume variation is computed first (ΔV_B^O) and then the following conditions are checked:

1) If $V_{BE,i}^O < V_{B,i}^O$ (or ΔV_B^O<0) there is onshore sediment transport, implying that the outer bar is releasing sediment towards the beach. In this case, the sediment will be transported to the inner bar. So, before computing the inner bar volume change based on its equilibrium value, the inner bar volume must be updated with the volume that comes from the outer, ΔV_B^O. In this situation, the total bar volume that will be transported to the berm will be given by the inner bar volume change (ΔV_B^I):

$$q_B(t)=\Delta V_B^I/\ \Delta T \tag{14}$$

2) If $V_{BE,i}^O > V_{B,i}^O$, there is offshore sediment transport and the outer bar is growing. In this case, before compute the inner bar change it is determined whether the inner bar volume has enough sediment to provide to the outer bar, *i.e.*, if $V_{B,i}^I > \Delta V_{B,i}^O$. If this condition is not met, the inner bar volume will disappear totally ($V_{B,i}^I$=0) and the remaining sediment needed to fill the outer bar will be transported from the berm.
3) If $V_{BE,i}^O > V_{B,i}^O$ and $V_{B,i}^I > \Delta V_{B,i}^O$ then the inner bar will provide the sediment needed to the outer bar. In this situation, the same procedure as in the case where there is onshore sediment transport is adopted, computing the sediment transport rate between the berm-bar regions as a function of the inner bar change.

In section 3.1 the two-bar evolution model just described is validated towards high-quality data collected at Duck, North Carolina, USA, which is a typical site where two longshore bars usually form in the nearshore.

2.2.3. Hypothetical bar equation for nearshore placements

Recycling appropriate dredged material resulting from inlet maintenance dredging operations and/or deepening activities of harbors is typically employed as a sustainable alternative to bypassing of sediment and maintaining beaches (Smith *et al.*, 2017; Marinho *et al.*, 2017a). In this context, for practical and economic reasons, placement of dredge sediment in the subaqueous portion of a downdrift beach becomes more attractive than in the subaerial zone, since dual underwater operations may be realized at considerably less time and cost, minimizing the effort required for positioning of the sediment (Gravens *et al.*, 2003). Also, the material placed in the nearshore need not to be exactly compatible with the beach sediments, because sorting induced by waves and currents will tend to drive finer sand offshore and coarser sand onshore (Larson and Hanson, 2015).

In the previous sections, a model based on empirical relationships was described as an attempt to simulate the evolution of individual longshore bars (or, representative morphological volumes), as well as the cross-shore exchange of material between the berm and the bar region. However, through the study of the response of natural longshore bars with respect to the incoming waves, it is possible to derive criteria that could be applicable for predicting the cross-shore evolution of mounds placed nearshore. In this light, outer bar is of particular interest because it is typically located in water depths where common dredging equipment can have access, allowing the placement of dredged material in the nearshore. Here, a simple approach is proposed to obtain a preliminary prediction of the migration rate of constructed sand mounds by numerically solving a hypothetical bar equation. In this study, the development of a criterion for predicting the evolution of nearshore mounds was based on the response of hypothetical outer bars subjected to transport by non-breaking and breaking conditions, that is, mounds placed within the surf zone, where the cross-shore morphological development can be dominated either by non-breaking or breaking waves. As a first approach, the study is focused on coastal systems with one natural bar (at most).

As demonstrated earlier, with the theory developed for systems characterized by the presence of two bars, different volumes can be modeled for the inner and outer bar. However, it was also shown that Eq. 6 can be employed when just one bar forms, where $V_{BE}^{TOT}=V_{BE}^{I}$ and $V_{BE}^{O}=0$. In such situations, the outer bar will attain an equilibrium bar volume equal to zero which, once nourished artificially with a certain volume (V_{B}^{O}), will gradually decay towards the equilibrium state described by $V_{B}^{O}=0$. Simultaneously, due to the bar-berm coupling system, a continuous widening of the beach (or shoreline advance) is expected to occur. Based on that, Eq. 12 can be rewritten:

$$\Delta V_{B,i}^{O}=-V_{B,i}^{O}\left(1-e^{-\lambda_i^{O}\Delta t}\right) \tag{15}$$

According to Eq.15, with $V_{BE}^{O}=0$ the condition $0<V_{B}^{O}$ will be always fulfilled, leading to an uninterrupted onshore-directed sand movement. According to Smith *et al.* (2017), the onshore migration of sand and beach recovery is a gradual process and only prevails during periods of low wave steepness. At the same time, it is considered that the offshore mounds may be exposed to a wide range of wave conditions, including wave breaking. However, the tendency for material to be transported onshore is much greater under the action of non-breaking waves in comparison with breaking waves (Larson and Kraus, 1992).

Another important factor to take into account when reproducing the evolution of a feeder mound is the depth of placement because the morphological responses occurring along the sloping sea bottom are expected to be different as a result of changing sediment transport rates (Ruessink and Terwindt, 2000). If sand is placed at the top or seaward of the breaker bar or even in a more offshore position, a different impact or at least a different time adjustment towards equilibrium should be expected (Bodge, 1994). Thus, a rational criterion or method is desirable to determine the overall response of the artificial mound for the incoming waves. Through the study of the response of natural longshore bars, in particular the response of outer bars, Larson and Kraus (1992) have proposed a procedure for predicting the cross-shore movement direction (onshore/offshore) of material placed in the nearshore zone intended to function as beach nourishment. These authors investigated different combinations of dimensionless parameters, such as, wave steepness, dimensionless fall speed and wave height over grain size diameter to develop a criterion that could distinguish accretionary and erosional events. Here, bar degeneration by depth-limited breaking waves is investigated through a simple approach based on wave height:

If $H_0<H_1$, then (calm wave conditions; non-breaking waves)

$$\Delta V_{B}^{O}=-V_{B,i}^{O}(1-e^{-\lambda_1^O \Delta t}) , \lambda_1^O=C_C^O\lambda_0 \tag{16}$$

Else $H_0>H_1$ (breaking conditions)

$$\Delta V_{B}^{O}=0 \tag{17}$$

where H_1 represents the wave height limit for the groups of waves that will break at depths where the outer bar is located. With the assumption that breaking waves are the main cause of bar formation and movement (or a limiting factor on the depth to the bar crest, h_c), the minimum depth over the bar should be of the same magnitude as the breaking wave height, H_b. Numerous formulas have been proposed to relate the breaking wave height to the water depth. Larson and Kraus (1989) found a relationship between the depth-to-bar crest (h_c) and the breaking wave height (H_b) based on analysis of profile change in LWT experiments:

$$h_c=0.66H_b \tag{18}$$

An example of how the profile may change the evolution of a nearshore sand mound for certain wave conditions is hypothesized. If the waves are small ($H_0<H_1$), it is assumed that non-breaking waves will act across the bar and the incident waves will break closer to the shore, promoting onshore sediment transport of the dumped material. During energetic conditions described by $H_0>H_1$, wave breaking prevails and the sediment transport will be considered to be offshore-directed, producing no variation in the offshore mound volume, $\Delta V_B^O=0$. Thus, during smaller waves the nearshore is intended to be "active" and designed to release sediments towards onshore, promoting accretion on the beach, whereas for wave heights larger than the breaking wave height, the nearshore mound is regarded to be stationary. As a way to take into account the typical cross-shore transport process on the nearshore mound, inducing dispersion or deflation in relief during non-breaking conditions, it is possible to assume that the material released from the mound go through the surf zone before ends on the berm, admitting in this way transport of the fill material to the inner bar (representative of the inshore portion of the profile).

In sections 3.2 and 3.3, field data sets collected at Silver Strand, California and Cocoa Beach, Florida (USA), in connection with field experiments involving nearshore placement of dredged material, are employed for model calibration and validation.

3. MODEL APPLICATION – CASE STUDIES

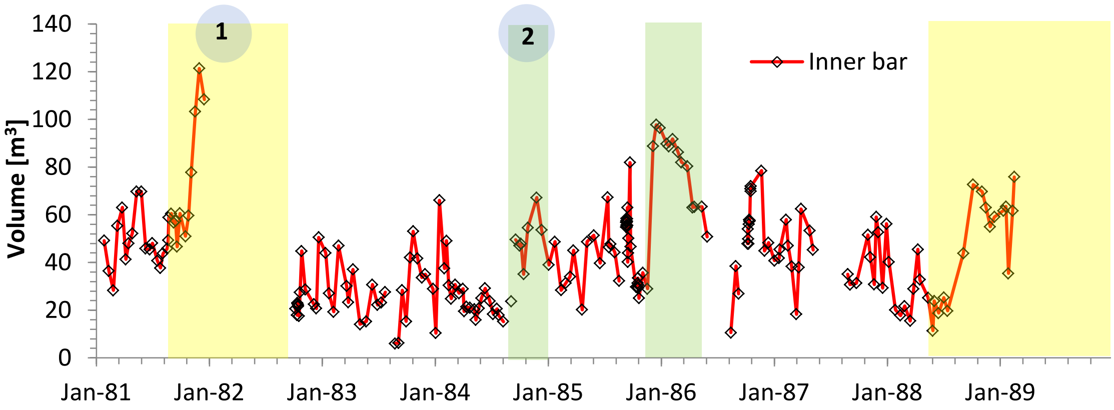
3.1. Duck, North Carolina, USA

3.1.1. Background and data employed

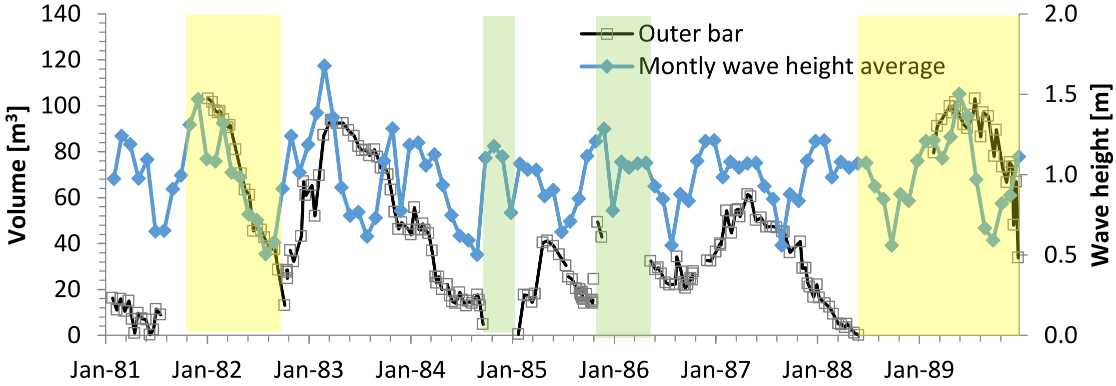
In order to illustrate the properties of the developed model, an example is provided to reproduce the evolution of two longshore bars (inner and outer) that usually appear in the nearshore at Duck, North Carolina, USA. Time series of waves and beach profiles measurements, collected 2-3 times per month by the Field Research Facility (FRF) of the U.S. Army Corps of Engineers, were used to model the volume of individual bars from 26-Jan-1981 to 28-Dec-1989.

The wave data employed were recorded with a waverider buoy located in 18 m water depth directly off the FRF research pier. Wave height was obtained as the energy-based significant wave height and wave period was determined as the period corresponding to the peak in the energy spectrum (Larson *et al.*, 2013). The nearshore bathymetry at FRF has been surveyed along four cross-shore lines located far from the disturbing influence of the research pier (Line 58, 62, 188 and 190, see Howd and Birkemeier, 1987). Since the general response of the beach profile to the prevailing waves at the four lines indicated similar long-term behavior, only data from Line 62, which has the most representative response in terms of bar movement and the largest number of surveys available (Larson and Kraus, 1992; Larson and Kraus, 1994), were considered in this study. Beach profile data related to Line 62 have been previously analyzed by Larson and Kraus (1992) to obtain detailed morphological properties of two bar features (inner and outer) with respect to a least-square fitted equilibrium profile to the computed average surveying profiles (including volumes and bar crest location). These data were considered here for model calibration and validation.

Overall, two measurements periods were identified by Larson and Kraus (1992) during which the inner bar consistently moved offshore to become the outer bar. These periods were observed just after the surveys of 28-Sep-1981 and 09-Sep-1988, where the offshore-moving bar became the outer bar. Although a distinction between the inner and the outer bar is appropriate for modelling purposes, this division is not straightforward. As referred previously, the cyclic behavior of multi-bar systems has been studied extensively. However, several nearshore morphological phenomena are still not well described. The inter-annual migration pattern of a bar and its relationship to the onset of a new inner bar is still poorly known. Recognizing the rudimentary knowledge for establishing relationships between aggregated short-term processes and phenomenological medium-term bar behavior in a quantitative way, in the two-bar model the inter-annual cyclic bar behavior is included *per se* (disappearance of the outer bar is implicitly described as the equilibrium bar volume can become zero). The buildup of the outer bar is taken as an intermittent process confined to the occurrence of high-energy periods ($H_0>H_c$). In the present study, the question remains under which conditions the inner bar, during its migration stage, should be recognized as the outer bar. For that purpose, the location of the bar was regarded as the decisive parameter. Based on the Larson and Kraus (1992) analysis of the FRF data, Figure 3 displays the volume and Figure 4 the bar crest depth for the inner and outer bars.



a) Inner bar



b) Outer bar

Figure 3. Volumes for inner and outer bar and monthly average of the measured wave height. Yellow shaded areas correspond to periods when the inner bar has migrated seaward to become the outer bar. Green shaded areas represent the periods when the outer bar has become flat, but reappearing after that at the same location. Numbers 1 and 2 highlight the periods of profile surveying that are further down displayed in Figure 5 and Figure 6, respectively.

Through analysis of the temporal variation in the observed outer bar volumes (see Figure 3), four cycles encompassing bar growth and decay can be identified during the measured period (1981-1989): 26-Jan-1981 to 17-Jul-1981, 07-Oct-1982 to 20-Sep-1984, 25-Jan-1985 to 21-Nov-1985 and 16-May-1986 to 02-Jun-1988. These time periods were based on the first and last survey revealing an identifiable outer bar feature for time series of consecutive surveys with an outer bar present.

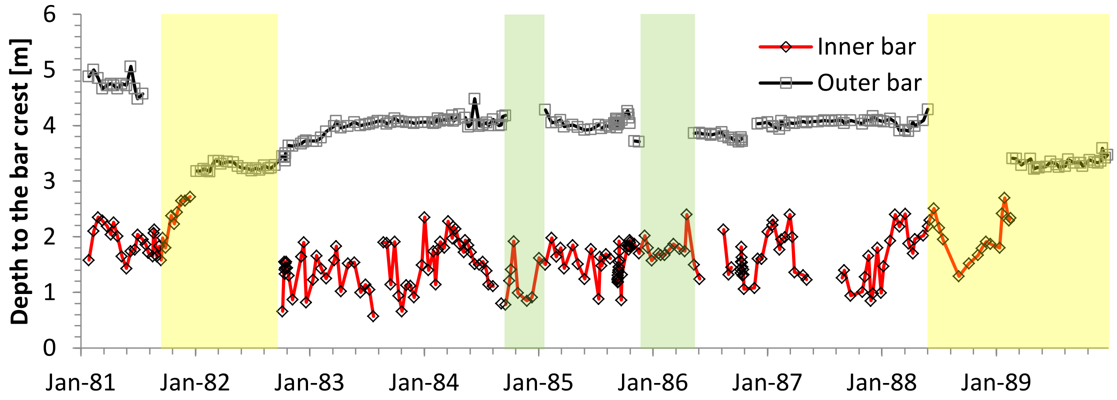


Figure 4. Depth of the bar crest for inner and outer bar. Yellow shaded areas correspond to periods when the inner bar has migrated seaward to become the outer bar. Green shaded areas represent the periods where the outer bar has become flat, but reappearing after that at the same location.

As previously mentioned, after the outer bar disappeared, the offshore movement of the inner bar to become the outer bar was observed during two periods: 28-Sep-1981 to 07-Oct-1982 (see Figure 5) and 09-Sep-1988 to 28-Dec-1989. Duck profile measurements have captured the termination of a bar cycle and the onset of the offshore migration of the inner bar from 28-Sep-1981 to 07-Oct-1982 and 09-Sep-1988 to 28-Dec-1989, providing an opportunity to evaluate the trigger point for a new cycle and its relationship to the outer bar response. Figure 5 displays times series of surveyed profiles collected between 28-Sep-1981 and 07-Oct-1982, where the onset of a new bar cycle can be distinguished: the decay process of the outer bar was followed by the onset of the offshore migration of the inner bar, thereby promoting the formation of a new bar near the shoreline.

The surveys indicated that the pronounced migration pattern of the inner bar appearing on the 28-Sep-1981 and 09-Sep-1988 (see Figure 3a), was preceded by a marked growth in the inner bar volume. According to Figure 3b, prolonged intermediate conditions (note that H_s presents a short range of variability), encompassing non- or weakly breaking conditions might be the main factor for the decay of the outer bar. The most distinctive part is that the outer bar became flat before the inner bar entered its migration stage. In fact, the inner bar only started to move consistently offshore when storms arrived at the coast, occurring during the autumn and winter season (see Figure 4 together with Figure 3). It seems that a shift in the forcing conditions was the triggering point for further offshore migration of the inner bar.

During the decay stage of the outer bar, significant fluctuations in inner bar volume and location were observed before the inner bar started to migrate consistently offshore. These fluctuations were attributed to the outer-bar decay condition yielding a more active inner nearshore bar zone. It was confirmed that even the offshore migration process is not a continuous phenomenon, but an intermittent process restricted to high-energy events. Small-scale fluctuations (onshore/offshore shifts of the bar crest) were observed when the inner bar approached the outer nearshore zone, proving that non-breaking conditions (see period of lower waves in Figure 3 together with Figure 4) have induced minor changes in the bar position.

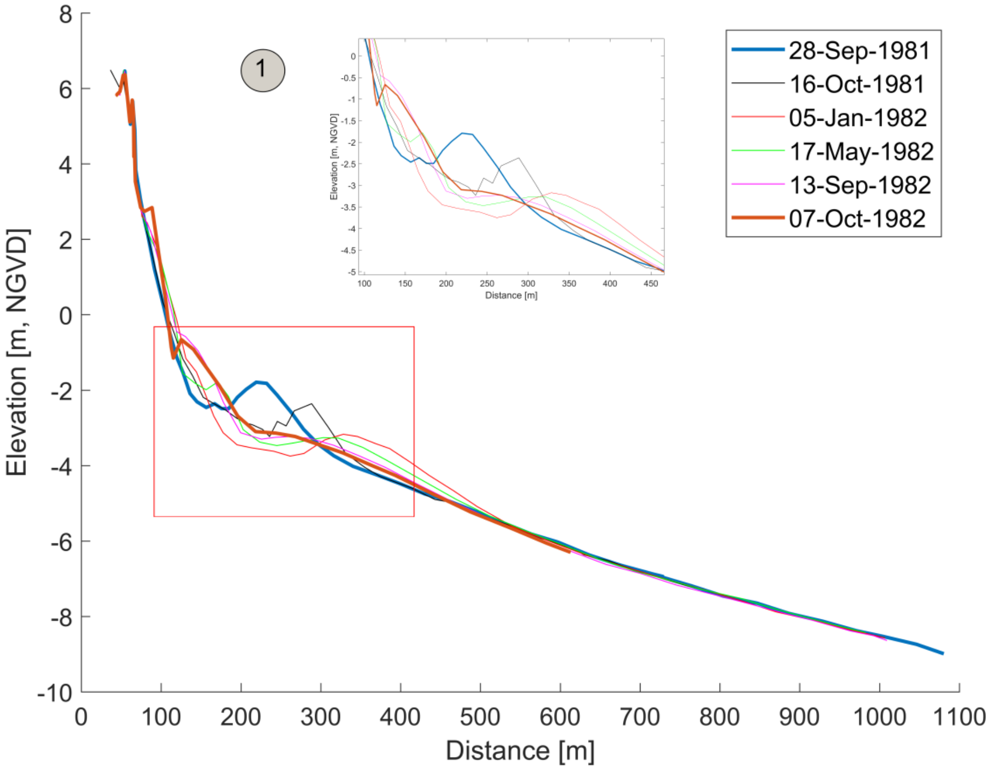


Figure 5. Surveyed profiles for Line 62 during the offshore progression of the inner bar to become the outer bar (28-Sep-1981 to 07-Oct-1982).

The decay and growth of the outer bar was also observed during 20-Sep-1984 to 25-Jan-1985 and 21-Nov-1985 to 16-May-1986. However, during these periods no evidence was detected in the surveys regarding a cross-shore progression of the inner bar towards the outer zone. Instead, the observations indicated that the outer bar has regenerated itself and reformed in deeper water (see Figure 6). It is hypothesized that this could be associated with more active sand transport promoted by a more frequent recurrence of breaking conditions, thereby affecting the transport and forcing of the outer bar, which starts growing (see large concurrent wave heights, Figure 3).

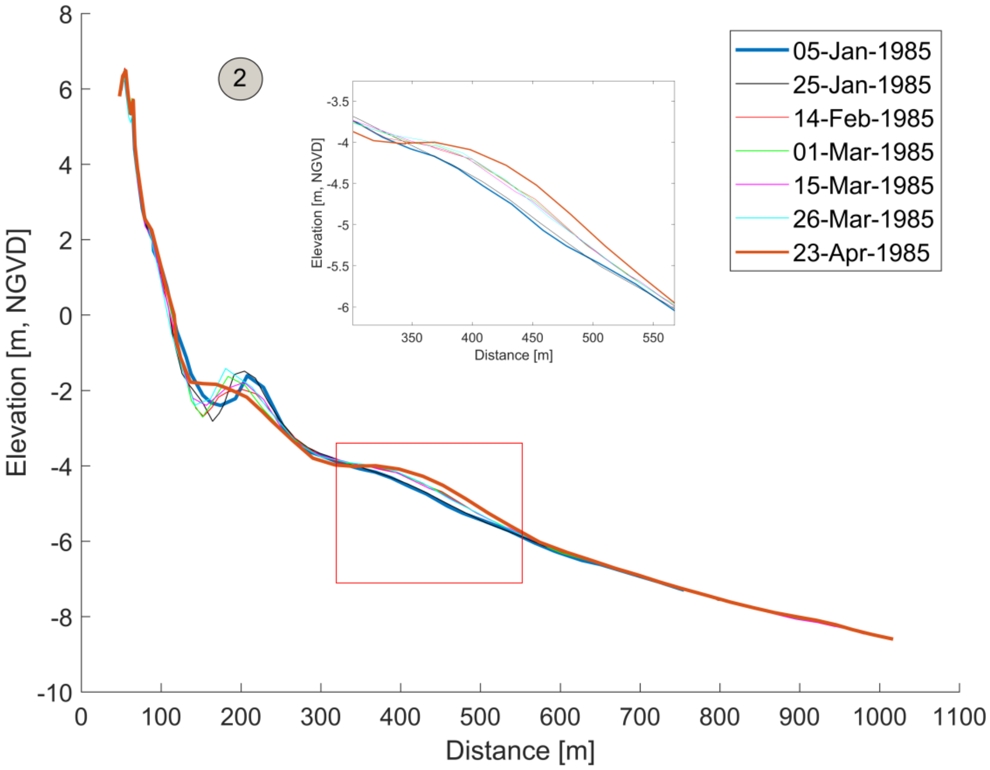


Figure 6. Surveyed profiles for Line 62 during the outer bar formation offshore (5-Jan to 23-Apr, 1985).

Comparing with the inner bar observations, Figure 4 shows that the fluctuations of the outer bar crest location are significantly smaller and much more regular (depth to bar crest is around 4m). Thus, it was decided that once a new bar has formed close to shore, and until it reaches the outer zone, the bar is considered to be an inner bar. In accordance with this criterion, bar measurements collected between 5-Jan-1982 to 13-Sep-1982 and 27-Feb-1989 to 28-Dec-1989 (periods during which the progressive bar experiences a stage described by small variations in position; see Figure 4), were assigned as outer bar observations. However, it has to be kept in mind that these assumptions were just defined for modelling purposes for comparing observations with the model results.

3.1.2. Model set up and calibration

The bar evolution equation (Eq.1) was applied to simulate the two-bar system behavior at Duck, where a numerical solution was employed following Eq. 6. The model was applied for the time period between 26-Jan-1981 and 28-Dec-1989, using wave measurements with a six-hour time step (Δt=6hr). The time series of the bar measurements were divided into two main periods, where the first one (extending from 1981-1985) was selected for calibration of the site-specific parameters (d_{50}, m, C_B, λ_0, δ_0, H_c) and the second one (from 1985-1989) was used for model validation. Test calculations demonstrated that employing a smaller coefficient to quantify the bar response rate of the outer bar relative to the inner bar yielded improved agreement between calculated and measured bar volumes. The coefficient values expressing the inner and outer bar responses were assigned to minimize the least-square error (ε) defined as,

$$\varepsilon=\left(\frac{\sum_{i=1}^{N}\left(V_B^{obs}-V_B^{cal}\right)^2}{\sum_{i=1}^{N}\left(V_B^{obs}\right)^2}\right)^{1/2} \tag{17}$$

where λ_0^I=0.0036 h^{-1} and λ_0^O =0.0023 h^{-1}, respectively. Based on many observations, including Duck (Figure 3), bars tend to form quickly during large storms, whereas during non-breaking conditions, the recovery process occurs slowly as a result of low transport rates. Also, since the inner bar varied more than the outer bar (see Figure 3), exhibiting a considerable sensitivity to changes in the nearshore wave conditions, non-breaking conditions are also expected to produce slower changes in the outer bar shape. Thus, a different multiplier (C_c) to reduce the coefficient λ_0 during onshore sediment transport was introduced in the simulations for both bars. The optimal values of this multiplier were set to C_c^O=0.15 and C_c^I=0.75 for the outer and inner bar, respectively. For the median grain size, d_{50}, the value 0.3 mm was specified. The dimensionless coefficients m and C_B were set to -0.5 and 0.08, corresponding to the optimal values obtained by Larson *et al.* (2016) when applying the model to different field sites. The water temperature was set to 15ºC. The initial bar volumes (t=0) were assigned to the initial observed values (calculated from the survey data), that is, 49.2 m^3/m and 16.2 m^3/m for the inner and outer bar, respectively. The empirical coefficient δ_0 was calibrated to 3 based on the observed typical relationship between the inner and outer bar volumes. The critical wave height H_c was assumed to be around 2 m for Duck beach. To test the model, two schematic cases were set up by admitting (or not) exchange of material between the two bars.

Herein, to evaluate the skill of the model, two definitions were used to discuss the dispersion of the model results: least-square error (LSE, ε, Eq. 17) and normalized mean square error (NMSE, Eq. 18). Normalized square error is defined as (Poli and Cirillo, 1993):

$$\mathrm{NMSE}=\frac{\overline{\left(V_B^{obs}-V_B^{cal}\right)^2}}{\overline{V_B^{obs}}\;\overline{V_B^{cal}}} \tag{18}$$

where the overbar parameters ($\overline{V_B^{obs}}$ and $\overline{V_B^{cal}}$) represent the time mean bar volumes over the observed and calculated values. According to Splinter *et al.*, (2018), general skill assessment can be made by: NMSE<0.3 (*excellent*); 0.3<NMSE<0.6 (*good*); 0.6<NMSE<0.8 (*reasonable*); 0.8<NMSE<1.0 (*poor*). The least-square was taken as a complementary index to measure the dispersion of the model performance.

3.1.3. Results and Discussion

Figure 7 illustrates the inner and outer bar volume variation with time and the agreement obtained with the observations during the calibration and validation periods, when no sediment exchange between the inner and outer bar was considered. The optimal parameter values found for 1981-1985, including the multiplier C_c for both bars, were used in the validation during 1985-1989.

Overall, promising results were achieved for the calculated outer bar volumes, yielding a least square error of ε=0.39, though the scatter obtained during the validation period was significantly larger compared with the calibration period (see Figure 7). The NMSE obtained for the outer bar was 0.24, considered as '*excellent*' (NMSE<0.3). For the representative total volume stored in both bars (ε=0.51, NMSE=0.24), trends in volumes were reasonably reproduced showing a good initial agreement between the two series, but developing discrepancies towards the end of the validation period, corresponding to the time when the outer bar decayed and the inner bar experienced offshore migration (with only one bar appearing). The same is verified for the outer bar volume, with the largest deviation occurring during the summer of 1989, when the inner bar moved seaward as a result of the storms hitting the beach during the winter 1988/1989. Also, mainly during Sep-1989 the wave periods were considered unusually long (with an average and maximum value of 10.6 s and 23.3 s, respectively) and judged to be outside the range for which the estimated parameter values would be applicable; thus, some events towards the end of the validation period should not be included in the comparison. It should be emphasized that the model confines the outer bar growth to high-energy events, for which the input critical wave height assumes a central role ($H_0>H_c$). This site-specific parameter describes a change in the forcing conditions characterized by a stronger net seaward movement that would act as a trigger for the onset of the outer bar formation.

Due to the considerable scatter in the observations of the inner bar volume, demonstrating a quite random behavior, part of the data were poorly reproduced, with a computed least square error ε=0.55 (NMRSE=0.33, '*good*'). This may be attributed to the fact that the inner bar is typically located within the region of breaking waves, where profile changes are more irregular and with a rapid response, challenging the predictive capability of the model. Limitations on the predictability of the inner bar behavior were also recognized by Splinter *et al.* (2018) when applying a simple equilibrium model to field data of observed sandbar position.

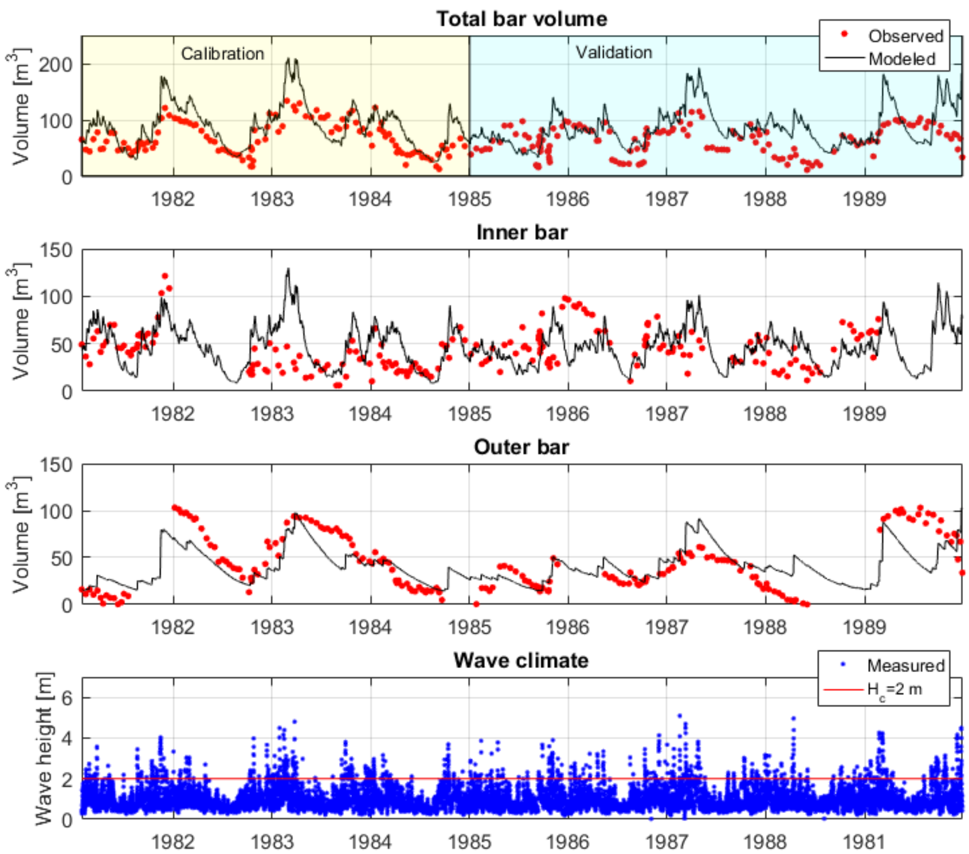


Figure 7. Total, inner, and outer bar volumes and wave climate (Duck, N.C.). Numerical

simulations without considering sediments exchange between the inner and the outer bar.

Overall, comparing with the previous simulations, results including an exchange of material between the inner and the outer bar (Figure 8) produced the same main trends in bar volume change, but displaying changes in the inner and total bar volume, decreasing the least-square error to 0.51 (NMSE=0.29, '*excellent*') and 0.46 (NMSE=0.19), respectively. The assumption that sediment transported to the outer bar are coming from the inner bar, tends to smooth things out, decreasing the amount of sediment mobilized in the subaqueous portion by the waves and reducing the estimated amount of sediment being transported through the interface between the berm-bar region. Although a scatter is still noticeable for the inner bar volumes, the trends for total bar volume are reasonably well described, with the predicted sum of the calculated bar volumes approximating the measured values. Thus, the exchange of material between the bars yielded improved agreement.

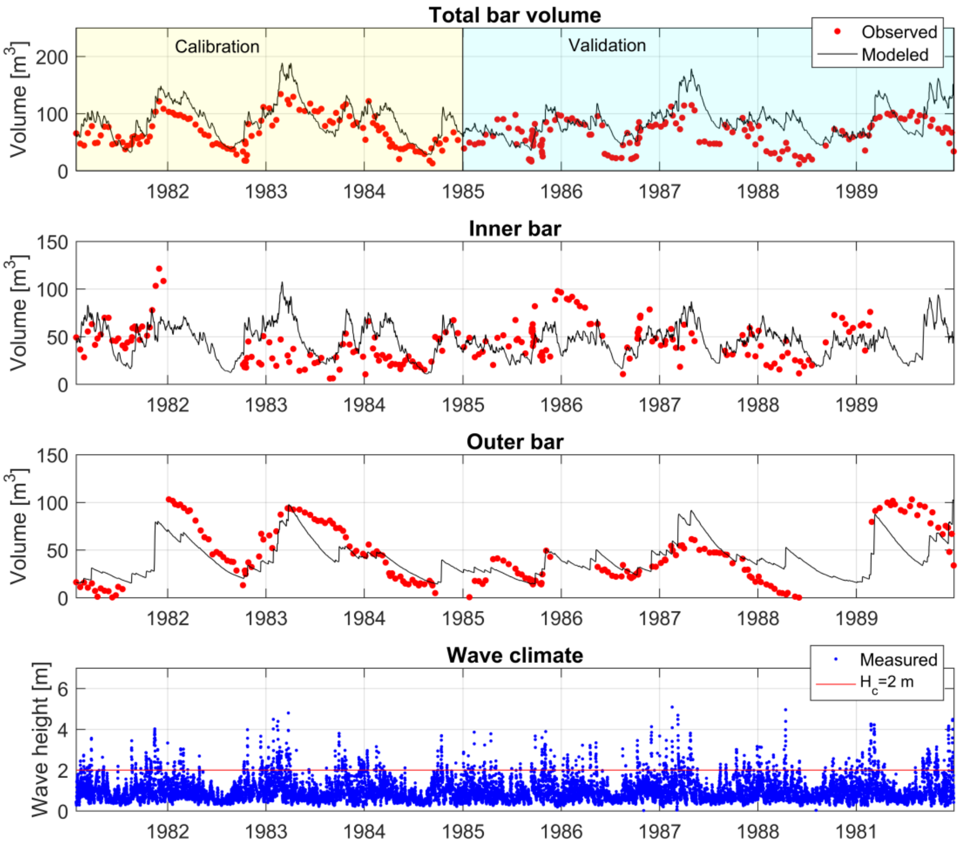


Figure 8. Total, inner, and outer bar volumes and wave climate (Duck, N.C.). Numerical simulations considering sediment exchange between the inner and the outer bar.

3.2. Silver Strand, Coronado, San Diego, California, USA

3.2.1. Background and data employed

The developed model for estimating the response of artificial nearshore bars intended to perform as feeder berms is here employed for reproduction of a field experiment carried out at Silver Strand, San Diego, California. During Dec-88, dredged material removed from the outer portion of the channel entrance to San Diego Harbor was placed in the nearshore zone off Silver Strand State Beach (located approximately 7.5 km southeast of the dredging site) as a means of supplying the beach and preventing further erosion. The inlet-dredged sand was disposed at the top of an existing bar, between water depths ranging from -3 to -9 m MLLW (Mean Lower Low Water), in the form of a rectangular berm with dimensions approximately 360 m alongshore and 180 m across shore, and an average relief around 2 m. The estimated dredged amount was about 113 000 m^3, corresponding to an incremental cross-shore volume of 310 m^3 per m of shoreline. The berm was composed of medium sized sand (d_{50}=0.18 mm) according to Juhnke *et al.* (1989), whereas the median grain size of the native material was approximately 0.25 mm.

After disposal, a follow-up program was set up to monitor the offshore mound response. Repetitive cross-shore surveys covering the placement area were performed during almost one year after the project was completed (from 9-Dec-1988 to 15-Nov-1989). In total, 9 field campaigns were carried out for 7 profiles (P1 to P7), in which four lines covered the initial location of the fill, and three were located southward. From the 9 campaigns, one was carried out just before (9-Dec-88) and one just after (29-Dec-88) the nearshore berm construction. These data have been earlier analyzed by Juhnke *et al.* (1989), Andrassy (1991), and Larson and Kraus (1992). According to Larson and Kraus (1992), who examined in detail several properties of the offshore bar through extensive profile data analysis, all the survey lines located across the placement site displayed similar behavior. Since Line 5 was located in the middle of the mound, where end effects caused by longshore transport should have been minimal, this line is used here in the model application. Figure 9 plots the surveys collected at Line 5 during the first completed year after the mound construction. Figure 10 displays the evolution of some nearshore bar properties (volume, maximum height, and depth to the bar crest) determined by Larson and Kraus (1992) by comparing the surveyed profiles with a derived equilibrium profile (obtained through least-square fitting of an equilibrium profile to the pre-construction survey).

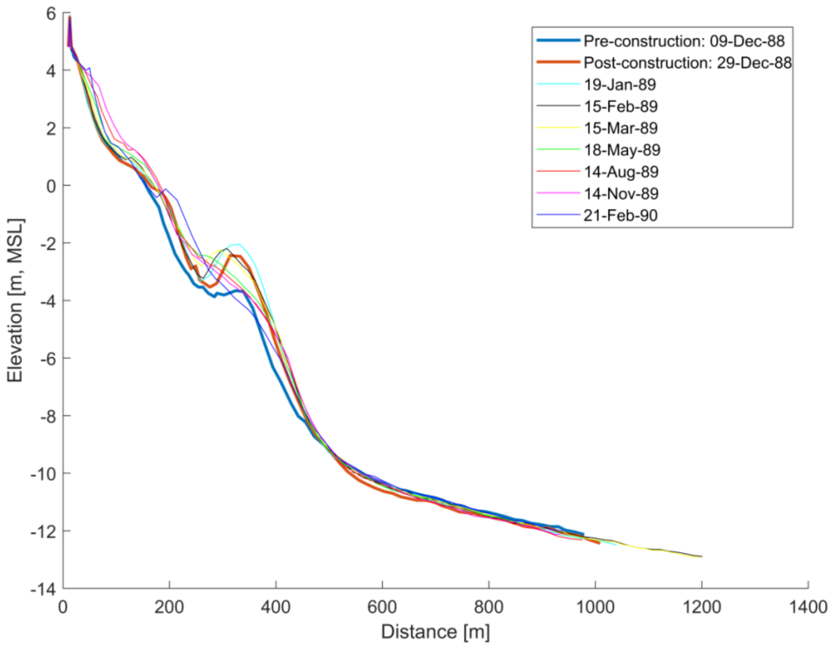


Figure 9. Surveyed profiles at Line 5 (during first year after berm construction).

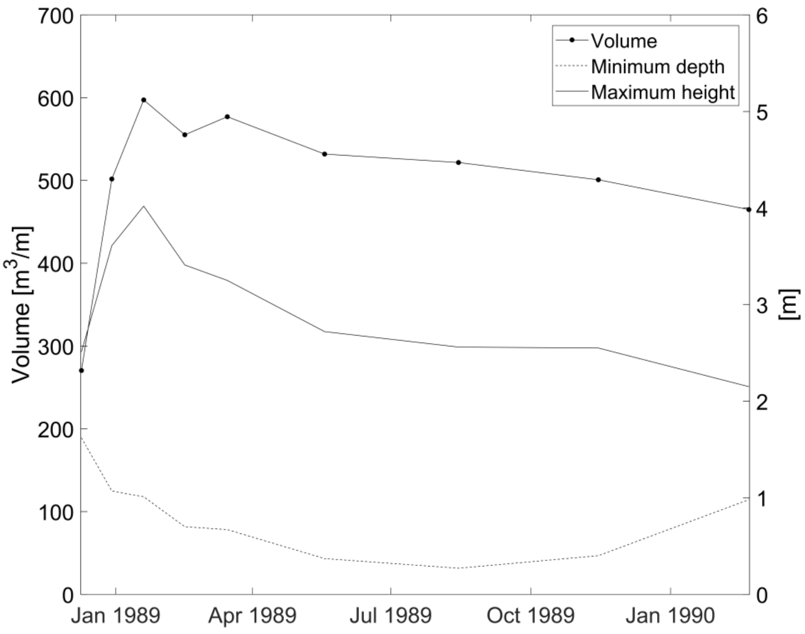


Figure 10. Evolution of the offshore mound properties with time (volume, maximum bar height and minimum bar depth). Depths refer to MLLW (= MSL - 0.85 m).

Overall, the profile change analysis indicated that the offshore mound has suffered a decrease in volume and height as the bar flattened out and migrated landward during the measurement period (see Figure 10). Larson and Kraus (1992) noted a general shoreward displacement of the mound center of mass, whereas the length of the berm showed an increase at first, thereafter followed by a slight decrease. The minimum depth at the mound firstly decreased, as the mound moved onshore, filling up the trough, afterwards exhibiting a slight deepening (see Figure 10). As shown in Figure 10, after the fill placement, the maximum bar height increased rapidly, but after about 5 months a constant value was approached, indicating that the bar primarily flattened out during this period – note the significant reduction in berm relief from 4.02 (Jan-89) m to 2.72 m (May-89). Although less marked, the volume change follows the same trend as the observed bar height, reaching its maximum in Jan-89 with almost 600 m^3/m. The increase in material occurring between 29-Dec-1988 and 10-Jan-89 derived from clean-up dredging and disposal operations that were still conducted during this period as a result of a couple of hot spots remaining in the channel. It was estimated that approximately 7 650 m^3 of sand was dredged for that purpose. However, according to Andrassy (1991) the highest fraction of the deposition registered between the post-construction and the following survey was likely related to some accretion of sand moving alongshore as a result of the creation of a relative low energy area in the lee of the disposal site.

Andrassy (1991) computed the volume change in three elevation zones (3 m to 0 m, 0 m to -3 m and -3 m to -10 m MLLW) in relation to the pre-construction bathymetry and observed a direct transfer of material from the original mound area towards the +3 m to -3 m MLLW region. Evidence from the surveying suggests that the flattening and onshore migration of the berm contributed to accretion of material along the inner portion of the profile.

3.2.2. Model set up and calibration

The empirical approach described by Eq. 14 was adopted to simulate the evolution of the mound created off Silver Strand State Park, for the time period of 9-Dec-88 to 21-Feb-90. The input profile was schematized based on the pre-construction survey carried out in 9-Dec-88. In order to investigate model performance two schematic cases were set up: 1) simulating the fill operation due to instantaneous addition of material to the existing bar volume (inner), adjusting the bar response rate with respect to the general response of the mound; and 2) modelling a representative morphological volume of the inner portion of the profile (described by V_{BE}^{I}=0), so that a transport of the fill material towards shallow depths, deriving from the flattening and onshore bar migration process, could be reproduced. Since wave measurements in connection with the surveys were only available for a limited time period (between 20-Jan-1989 and 18-May-1989), hindcasted wave data were employed in the simulations for the missing period. The model time step was set up based on WIS (Wave Information Studies) wave information, available every 3 hours. The initial bar volume, $V^{I}_{B,initial}$, was set to the measured value of 270 m^3/m at 9-Dec-89. Also, an extra cross-sectional fill volume of 71m^3/m was added to the simulations to represent disposal operations and longshore volume variations that occurred between 29-Dec-88 and 19-Jan-89. The median grain size of the fill material was somewhat finer than the native sand (0.25 mm) along the nourished portion of the profile, so a value of 0.20 mm was adopted for d_{50}. This value was also used by Larson and Hanson (2015) when modeling mound diffusion at different sites (including the Silver Strand site) using a one-dimensional diffusion equation. The water temperature was specified at 15ºC, and the same values on m and C_B from Duck were used for Silver Strand. The values of the remaining site-specific input parameters were mainly determined by comparing results and trends of changes in bar volume in order to obtain the lowest value on ε for both the schematic cases. The optimal value on λ_0 that yielded to the best agreement between the measurements and model results was 0.002h^{-1}, whereas for C_C a value of 0.10 and 0.20 were considered for the first and second case, respectively. Based on the average value of the minimum depth to the bar crest, in the latter case, a wave breaking height H_1=0.8 m was specified to identify events when sand is transported onshore across the inshore portion of the profile.

3.2.3. Results and Discussion

The bar transport model was successfully employed for the one-year simulation period; the pattern of landward migration of the offshore mound could be reproduced for the studied profile. The results of the simulations are here presented and evaluated by comparing the computed bar volumes with the values on the offshore bar volume estimated from surveys (see Figure 11 and Figure 12).

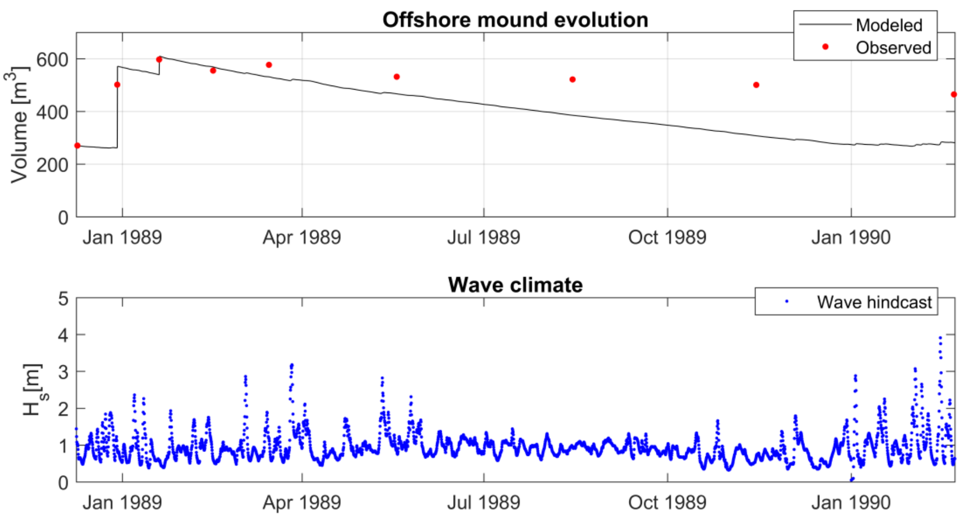


Figure 11. Nourishment evolution simulation by adding extra volume to the existing bar (Silver Strand, Coronado).

Figure 11 displays the simulation results obtained when directly adding material to the existing bar. As seen in the figure, discrepancies develop towards the end of the simulation period, as the measured bar volume exceeded the predicted values. The computed error was $\varepsilon=0.26$ (NMSE=0.09), with an error for the last four data points computed in $\varepsilon=0.30$ and NMSE=0.12. The observed data points indicate that a large part of the fill material still remains at the site placement area, revealing that the model release the fill material from the bar towards the beach somewhat too quickly. The onshore transport of material captured by the surveys, exhibiting a gradual lowering of the maximum bar height, as well as an increase of material in the inshore portion of the profile might be a possible reason for obtaining these deviations (see Figure 5 for the natural behavior of the natural bar). In fact, in the numerical model simulations, the fill material is transported by the waves directly to the beach (decay in the bar implies a growth of the beach width), which is not in agreement with the observations, since part of this material appeared to go through the surf zone before ending up on the beach.

Figure 12 shows the model results when simulating a hypothetical inner feature to better account for the transfer of material across the surf zone. In this figure, the natural evolution of the nourished bar is represented by the continuous black line (computed with respect to its equilibrium state). The green line represents the evolution of the hypothetical feature which depend on low-energy events ($H_0<H_1$) to transport the fill material to the beach. The dashed line corresponds to the sum of the modeled values for the inner portion volume and the nourished bar volume. Although the surveys have indicated a mixed response between the existing bar and the fill volume (moving as an

unique identifiable unit), the calculations demonstrate that simulating the impact of flattening mound process by incorporating a hypothetical inner feature produced significant improvement, especially during the final part of the study period where measured and modeled values agree well, yielding a lower total error of ε=0.18 (NMSE=0.03, considered '*excellent*'). Also, the trends are satisfactorily described, making the reproduction of the measurements better than in Figure 11.

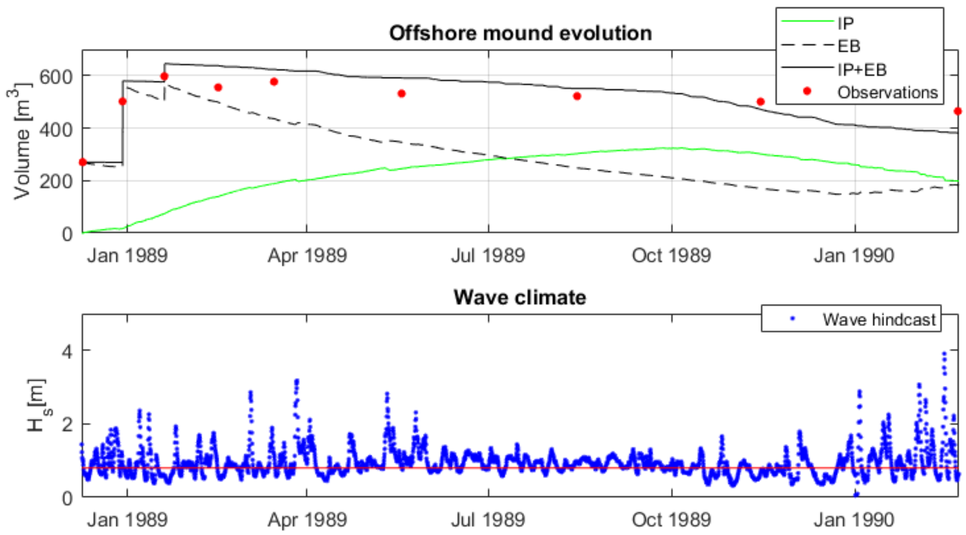


Figure 12. Nourishment simulation using a hypothetic inner bar (Silver Strand, Coronado), where IP and EB are acronyms for Inshore Portion and Existing Bar (nourished with dredged material), respectively. Red line represents a threshold for the wave height that controls when sand is transported landward, from the inner portion of the profile to the berm (H_1).

3.3. Cocoa Beach, Canaveral, Florida, USA

3.3.1. Background and data employed

In the Silver Strand case, the simulations of the underwater nourishment response (*e.g.*, through the modelling of a hypothetic bar; defined as V_{EQ}=0) were performed for coastal systems where natural bars frequently appear. In order to simulate coastal systems where no longshore bars were monitored during the surveyed period, the same procedure can be adopted. As the formation of longshore bars is the natural profile response to storms (*i.e.*, large breaking waves), for such coastal systems the volume change in the subaqueous portion of the beach profile may be significantly lower when compared to systems that exhibit such impact. This behavior can be described by V_{BE}^{O}=0 together with V_{BE}^{I}=0, if also the inner bar is absent.

Here, the model applicability in predicting the evolution of a sand bar artificially implemented at Cocoa Beach (Florida, USA), a coastal area characterized by the absence of natural breaker bars, is demonstrated. Dredged sand from 1992-1994 maintenance activities at the Port Canaveral Entrance channel was placed in a nearshore disposal area offshore of Cocoa Beach (8.4 to 11.3 kilometers southward of the source), in order to retain beach-compatible sand in the littoral system. The intent of the federal maintenance dredging project, involving disposal of the dredged material downcoast, was to minimize local beach erosion (mainly attributed to the presence of the inlet), by constructing a shore-parallel bar within the active littoral zone that could benefit directly or indirectly the shoreline. The fill activities started in 1992 (from 6-June through 24-Jul), involving the deposition of 121 000 m^3 of sand. In 1993 and 1994, more disposal activities were undertaken, implying a total sand volume mobilized of around 263 000 m^3. Although bathymetric data were collected to document the evolution of these interventions, surveys covered different areas along and across the shore. Thus, after data censoring, just a specific set of high-quality monitoring data related to the first intervention (1992) were selected for model application. This data set encompasses five bathymetric surveys collected for several lines alongshore, spaced about 40 to 75m apart, intercepting the placement site. These lines were surveyed before (pre-project, Jun-1992) and after the fill placement (post-project, Jul-1992) and then on three different occasions until one year after construction was completed (Dec-92, May-93, Jul-93). The data collection extended from 45m seaward of the disposal area to about 245m landward thereof, or from the -8.4m to -3.4m MLW (Mean Low Water) depth contours. According to Bodge (1994) the permitted nearshore disposal area of 1992 was defined 2 895m in the longshore direction and 200 to 245m wide in the cross-shore direction. Figure 13 depicts the surveyed profiles along two distinct lines: one located in the northern part of the designated placement area and the other in the southern part, where no fill material was placed during the first disposal.

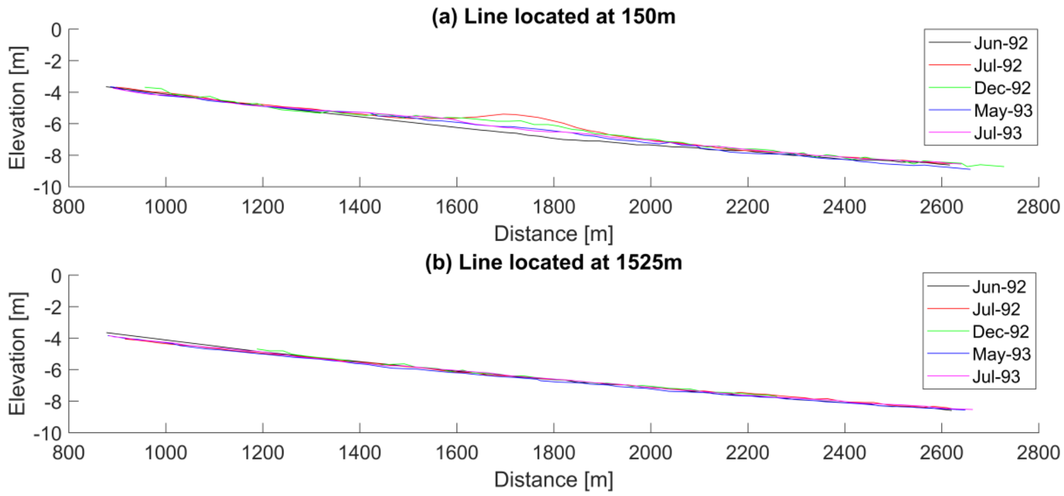


Figure 13. Selected survey profiles intercepting the permitted disposal area (0m to 2 895m in the local alongshore coordinate system): (a) northern part and (b) southern part.

Although the authorized disposal area extended alongshore from station 0 southward to station 2895 (0m to 2895m in the local alongshore coordinate system), inter-survey data analysis along this area showed that the nourishment activity focused in the north, from station 0 to about 815m southward. This is in agreement with Figure 13, where the seabed changes of the most northern-located profile (Figure 13a) demonstrates that the initial bar was constructed here, while no pronounced bar is observed in the southern disposal area (Figure 13b). Thus, since the nourished sand was not uniformly distributed alongshore in the permitted dumping area, six northern evenly-spaced profile lines were selected to evaluate the seabed changes associated with the nearshore bar. For each survey event, the average depth of these six profile lines (intercepting the disposal activity) was computed; the evolution in time was thereafter compared within the same cross-shore surveyed area (located between 320m and 790m – distance to an artificial baseline being approximately the NGVD – National Geodetic Vertical Datum – shoreline). Since the first survey was carried out before the fill placement, the corresponding average profile was designated as the "background" (or "pre-project") profile. Figure 14 plots the average profiles computed for each survey event that occurred between 16-Jun-1992 and 1-Jul-1993.

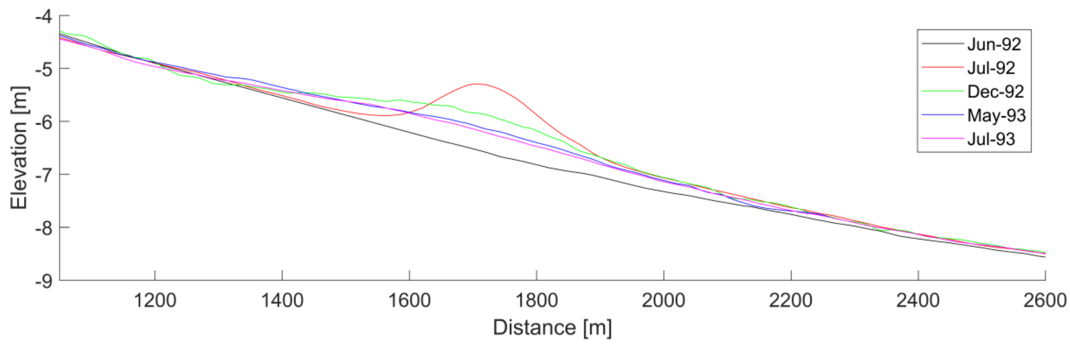


Figure 14. Average profile evolution at northern disposal area (0m to 800m). Distance along the profiles refers to an artificial baseline set at approximately the NGVD shoreline. Elevation in relation to NGVD.

In Figure 14, an artificial nearshore bar can be recognized just after the placement (Jul-92), as well as a subsequent pronounced landward migration of the mound during the following months (Dec-92; May-93; Jul-93) accompanied by a clear shift of the bar crest towards shallower waters. Also, the bar height experienced a significant reduction during the first 5 months after the dredged material was placed, corresponding to the period when most of the flattening occurred. Thereafter, the bar relief decreases more slowly, with the bar almost welding on the shore in Jul-93. Overall, the onshore movement of the artificial bar resembles a cross-shore diffusion process, influenced by a shoreward-directed advection. Thus, the flattening and onshore movement of the mound contributed to the accretion of material along the inner portion of the profile.

3.3.2. Model set up and calibration

The model was run for a year, from 16-Jun-1992 to 01-Jul-1993. As in Cocoa Beach, no natural bars were monitored, the numerical model was set up to reproduce the behavior of the nearshore mound disposal through the simulation of a hypothetical feature defined by $V_{BE}^{O} = 0$ (representing the outer portion of the profile). In line with the Silver Strand study case, to improve the agreement with the observed mound response (Figure 14) and to better reproduce the transport of the fill material through the surf zone, a representative morphological volume for the inshore area was included in the simulations. This morphological feature, included to describe the exchange of material between the subaqueous bar and shallower portions of the profile, was considered to behave in the same manner as the outer bar, implying a second threshold value for the wave breaking height, H_{b2}, intended to control the nearshore activity. Both equilibrium volumes are set to be zero and thus, this exchange of material is considered to be onshore-directed. Since no wave measurements were made in connection with the profile surveying, a wave hindcast with a 3-hour time step was used in the simulations. Model calibration was performed by adjusting site-specific input parameters and estimated values based on the pre-surveyed profiles and previous studies. According to Bodge (1994), the median grain size of the pre-disposal seabed was 0.104 mm, whereas samples of seabed during and after the disposal activities indicated a representative median diameter around 0.40 mm. As the native grain size differed significantly from the nourished sand, an average value of 0.21 mm was adopted for d_{50}. The water temperature was specified to 26ºC. The same parameters values on m, C_B and λ_0 used for Silver Strand were kept for Cocoa Beach. The optimal value on the multiplier (C_C) employed to reduce λ_0 was 0.2. Wave heights thresholds of 4.2 m (H_{b1}) and 2.0 m (H_{b2}) were specified to determine onshore movement of material from the outer and inner portions of the profile, respectively, for periods when the offshore wave height does not exceed these values. To validate the model, comparisons were made with measured profiles.

3.3.3. Results and Discussion

The model results were quantitatively evaluated by comparing the computed bar volumes with the values estimated from the surveys. Figure 15 depicts the time variation in the calculated bar volume, as well as the agreement obtained between the measured and the predicted values during the first year after nourishment operations.

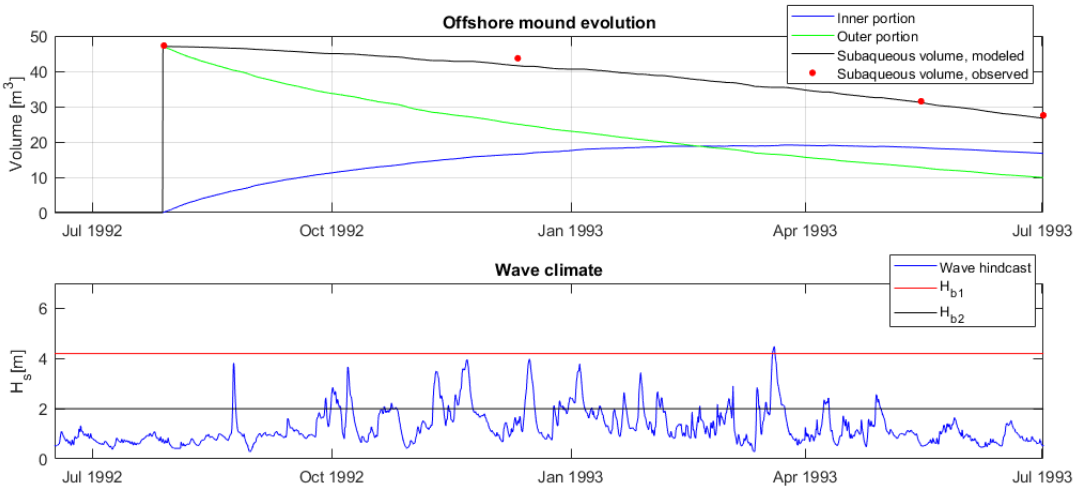


Figure 15. Results of the nourishment simulation using a hypothetic outer bar (Canaveral, Cocoa Beach) considering exchange of material with the inner portion of the profile. The green shaded area represents the period of measurements.

The model prediction is judged to be good by considering the transfer of fill material towards the shore through the most inshore portion of the profile. The obtained error was ε=0.03 (NMSE=0.001, '*excellent*' agreement). At the same time as the outer bar started to release sediment, the inner portion filled up as the wave forcing was favorable for such conditions (note that the wave climate was quite energetic during this period). A shift towards low-energy wave conditions (reflected by a general decrease of the values of H_s) appearing simultaneously with the maximum inner volume (Apr-93) suggests a change to a negative sediment budget at the inshore part of the profile, where the volume transported from the outer zone to the inner becomes lower than the volume transported from the inner portion to the beach (see Figure 15). This behavior is in agreement with Figure 14, where the major modifications of the mound shape took place during the first 5 months just after the fill placement (between the "post-survey" and Dec-92), while during the next period (Dec-92 to May-93) a higher volume loss occurred. Overall, the time adjustment of the profile towards an equilibrium state is being properly described by the model, as well as the volume time variation during the measurement period.

4. CONCLUSIONS

An extended version of the heuristic model, first introduced by Larson *et al.* (2013), designed to calculate bar-berm material exchange, was developed here for application in coastal evolution models that describe processes at the decadal scale. The model was enhanced to reproduce the overall shift in material between the subaerial and subaqueous portions of the profile by taking into account the long-term evolution of multi-bar systems and the response of offshore mounds placed in the outer part of the nearshore zone to act as active or feeder bars (for beach nourishment purposes). The model is based on simplifications of the governing processes, where bar volume evolution determines the transport direction, *i.e.*, bar growth implies offshore sediment transport and bar decay corresponds to onshore sediment transport. As a first attempt, efforts were made to simulate coastal systems with up to two longshore bars appearing in the nearshore, where both growth and decay of individual bars are computed with respect to a representative subaqueous morphological volume, or total bar volume, defined at equilibrium. The presented two-bar model, rather than resolve the fine details of the profile response (or bar shape), relies on a simple approach to compute volume changes distributed between the two bars, with the assumption that larger waves result in more material in the bars compared to smaller waves (quantified based on data).

Before combining the developed model with modules resolving the subaerial processes and the interaction with the berm (dune erosion and overwash, dune build-up by wind etc.), the model was calibrated and validated in standalone mode at three field sites from the United States: 1) Duck, NC, where two natural longshore bars (an inner and outer bar) typically form; 2) Silver Strand, CA, where a nourishment was placed on top of an existing bar; and 3) Cocoa Beach, FL, where an offshore feeder mound was located in deep water, where no natural bar exist. It was shown for the Duck case that the response of the outer bar was significantly slower than the inner bar to changes in the cross-shore sediment transport. Thus, non-dimensional multipliers (or coefficients) in the empirical transport relationships had to be determined based on the data. Overall, equilibrium volumes and rate-of-change coefficients were related to non-dimensional wave and sediment properties (*i.e.*, wave steepness and non-dimensional fall speed), but during the calibration certain coefficient values had to be obtained through comparison with data and subsequently validated. Although the criteria presented here should provide a first rough estimate of suitable values, parameters such as the critical wave height and wave breaking height (used to define the wave heights thresholds) determining the outer bar formation and the response of mounds, respectively, are expected to be site-specific and data are needed to apply the model with confidence at a particular site.

One of the challenges at understating and predicting multi-bar behavior was the book-keeping of individual bars. The low temporal resolution of the data employed for Silver Strand and Cocoa Beach case studies (approximately one year) was considered a limitation to this study. Modelling of multi-bar system is complicated when bars merge and migrate both in time and cross-shore. Bar merging is more common during transition periods (winter-summer or summer-winter) and also linked to nourishment operations. Bar migration has been mostly linked to situations with severe surf zone conditions promoted by high-energy events. Such mechanisms are expected to impact the bar behavior. However, the cyclic behavior of barred systems (happening on the time scale of years) was implicitly accounted since a growth in the outer bar volume is associated with a net seaward movement of sand and a decay in the outer bar volume is caused by onshore sediment movement (tending to degenerate the outer bar). The model treats each bar as a discrete entity, allowing also feedback from adjacent features, although the migration of individual bars is not captured by the model.

Despite these shortcomings, the model application showed that the equilibrium model is skilled at predicting the time-varying volume of the outer bar, suggesting that this morphological feature is strongly influenced by offshore wave forcing in a predictable, equilibrium-forced manner (ε=0.39; NMSE=0.24). Model skill was lower when predicting the inner bar evolution due to the scatter of the observations although based only in NMSE index an overall good agreement with the observations was achieved. It is yet to be explored if the inner bars in a multi-bar sites display predictable, equilibrium driven cross-shore behavior, similar to outer bars and shorelines. As discussed previously by several authors (Splinter *et al.*, 2018), the behavior of the inner bars is hypothesized to be more conditioned by changes in the tide range and act as sediment transport pathways between the shoreline/berm and the outer bar.

Overall, the present study demonstrates the potential for using rather simple models, underlying the definition of some equilibrium state that is compared to the current state and some magnitude of forcing available to drive the changes in the profile. The methodology employed here allowed to quantitatively reproduce the main trends in the subaqueous beach profile response in a long-term perspective as a function of the bar volumes disequilibrium, the magnitude of the incident wave height and the dimensionless fall velocity to move the sand with a time-varying forcing term outside the disequilibrium term. Duck measurements have detected that some bars form in the nearshore and move all the way offshore (eventually deflating by non-breaking waves). At the same time, it was equally observed that a lot of inner bars form in shallow water do not move offshore, but remain as inner bars all the time. According to this, the developed model considers that the inner bar will not become the outer bar, but material previously dedicated to the inner bar will be available for the outer bar.

It was also shown that the model has applicability for predicting the evolution of nearshore mounds that migrate towards the shore and become part of the beach face by the action of waves and currents, through the simulation of hypothetical bars defined by zero equilibrium bar volume. This modelling approach could be more widely applied to other beaches to explore shoreline equilibrium behavior, by merging it with a shoreline evolution model, or combining it with a compatible dune erosion module to simulate beach berm response and illustrate its applicability in predicting seasonal changes, as well as the supply effects at medium-term related to the fill project on the shoreline position.

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